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Forces Exerted on Restraining Structures
by Hog Fuel Piles

by

W.C. Edwards and P. Tam

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September 1982

ABSTRACT

Extensive experience has been gained with the design of retaining walls for soils and fill materials having a granular nature. However, doubt exists as to the applicability of this experience to the design of retaining walls for wood residues.

Field tests were conducted under ordinary plant operating conditions to measure the lateral pressure imposed on a retaining wall by piles of wood residues in chipped and hogged form. The effects on lateral pressure of the height, shape and age of the pile, bulk density of the residues, and vehicle traffic on the pile were investigated.

From tests with a conical green chip pile, lateral pressure was found to vary non-linearly with depth and to vary in differing proportion to depth, depending on the pile size. The coefficient of active horizontal pressure, k_{ah} , was determined to decrease to 0.42 as the pile height above the lowest sensor reached 3 m.

Values of k_{ah} were determined for hog fuel resting against a plane bin wall. The average value of this coefficient was 0.5 over four runs with pile heights above the sensor increasing to about 5.5 m. Pressures varied non-linearly with depth, and also were dependent on pile size.

Experimental values of k_{ah} were compared to theoretical values predicted by the Coulomb equation for a wall with friction. The best comparison resulted when the internal friction angle was assumed near to the observed average surface slope of the pile.

A minor effect of age on pressure was observed for tests with an outdoor 3.55 m-high hog fuel pile having a flat surface. Pressures decreased during the first few days and subsequently stabilized.

A series of tests were conducted by moving a small bulldozer parallel and perpendicular to a retaining wall in front of pressure sensors. Measured lateral pressures compared favorably with that predicted by theory at a depth of 0.681 m, but were considerably lower than the theoretical values at greater depths.

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NOMENCLATURE AND DEFINITIONS

A. NOMENCLATURE

- H - pile height (m)
- P - pressure (kPa)
- k - coefficient of pressure (stress)
- M.C. - moisture content (%)
- w_b - denotes moisture content on a wet basis
- $\bar{x}$ - mean value
- σ - standard deviation
- γ - packed weight density of solids (kN/m³)
- ϕ - internal friction angle (deg.)
- β - pile slope (deg.)
- α - angle of retaining wall with horizontal as shown in Figure II-2 (deg.)
- θ - wall friction angle (deg.)
- δ - wall deflection (mm)

Subscripts:

- h - horizontal component
- v - vertical component
- a - active state
- p - passive state
- o - at rest
- w - at wall

B. DEFINITIONS

$$\text{Moisture Content, wet basis} = \frac{\text{wt of wet sample} - \text{wt of dry sample}}{\text{wt of wet sample}} \times 100\%$$

Packed Weight Density = sample density in kg/m³ times the acceleration of gravity, 9.81 m/s², to give weight density in (kN/m³). An arbitrary standard method was adopted for determining packed weight density. The sample volume was determined after packing by dropping the sample container five times from a height of 15 cm onto a nonresilient surface. All densities given in this report apply to solids in the packed condition.

Thrust = Total load on a retaining wall per unit width of wall due to pressure from solids (kN/m).

I. INTRODUCTION

A. Background

Numerous theoretical analyses are presented in the literature for loads imposed on retaining structures by cohesive and cohesionless materials, usually soils and similar fill materials. Experimental data are available to establish design parameters for retaining these materials with acceptable confidence. However, there is a lack of comparable data for design of retaining walls for cohesive wood residues commonly handled at forest products mills.

Instruments and procedures have been developed for measuring pressures imposed by soils on retaining walls. None of these have, to date, been used for wood residues, and their suitability for this duty was not known prior to this study.

To potentially reduce the cost of retaining structures (both bin walls and retaining walls) for wood residues, which at present are relatively high, experimental data are required for typical industrial applications. This cost reduction would accrue from savings in materials and labour that could potentially result from a better understanding of the loads imposed by wood residues, making it possible to optimize the design.

B. Scope

The work undertaken in this study involved the measurement of lateral pressures imposed on retaining walls in use at two sawmills. Specifically, the objectives of the work were:

- in an industrial installation, measure the lateral pressure imposed on walls retaining coarse wood residues, in particular, hog fuel;
- determine lateral pressures developed by the pile as it is built-up and drawn-down;
- determine the effects of vehicles, such as bulldozers, operating on the pile;
- determine the variation of pressure as the pile ages;
- determine the variation of lateral pressure with depth in the pile;
- produce data in a form which will provide design engineers with a basis for designing walls to retain wood residues, and which will

indicate areas where further study is required to refine design techniques.

The study was conducted in two phases. Phase I concentrated on the selection and design of pressure-sensing and recording instruments, followed by a limited series of tests to monitor the pressures near the base of a wall retaining hog fuel. Phase II of the work concentrated on applying the instruments developed in Phase I to gather most of the pressure data for the various loading conditions stated in the objectives above.

II. THEORETICAL BACKGROUND

A. Approach to Design of Retaining Walls

Retaining walls are structures used to form a permanent wall for support of soils, gravel, coal, wood residues, and almost any other granular or fibrous material where space or design does not allow the material to reach its natural angle of repose. Retaining walls are constructed of concrete, wood, steel, or other structural materials as dictated by the applied loads, permanence of the structure, and cost.

Most of the published analyses for the design of retaining walls deal with support of soils, gravel, and other fill materials. Design data are consequently oriented toward the mechanical properties of sands, clays, and soils. Some references for this subject area are Lambe and Whitman (1969), Paaswell (1920), and Reimbert and Reimbert (1974).

Using the same fundamental approach as for soil mechanics, considerable analysis of the design of silos containing granular materials has been done. One reference for a summary of this work is Reimbert and Reimbert (1974). Work in this area has considered the design of silos of various cross-sectioned shapes, wall designs, and capacities. The relationships for silo design, although somewhat similar to those for retaining walls, differ as a consequence of the complete containment of the solids. As the diameter of the silo increases, the relationships approach those for retaining walls.

In this study we were concerned with the lateral pressure imposed on a retaining wall by a pile of wood residues in chipped and hogged form. The pressure imposed on the wall is due to the weight of material placed against the wall that is at locations above the natural slip angle for the material under the conditions present within the pile. The difference between these pressures and what would occur for soils or other materials is a direct result of the differences between the mechanical properties of these materials. To the present, the design of retaining walls for wood residues has been severely hampered by the lack of test data defining the mechanical properties of wood residues that are needed for design purposes, and that would justify the use of relationships presently being applied to design of retaining walls for soils. Prior to this study, it was not known whether the existing design relationships for walls retaining soils could be used with confidence for design of walls retaining wood residues having markedly different mechanical properties.

B. Design Relationships

Classical analysis of forces imposed on a retaining wall is founded on the basis of a linear increase of pressure with increasing depth,

this being analogous to pressure developed by a fluid. The pressure at any depth of pile, H , is given by the general relationship:

$$P = k \gamma H$$

where γ is the bulk density of the solids and k is the coefficient of pressure. When the retaining wall is deflected by the pressure of the retained solids and the full shear stress of the material along with the slip plane is mobilized, the wall is supporting the active thrust, and the coefficient of active pressure, k_a , is used. If no deflection of the wall occurs, the coefficient of pressure at rest, k_0 , is used. For the last case when the wall exerts pressure on the retained solids, the coefficient of passive pressure, k_p , is used. The states of pressure at the two extremes of active and passive conditions are called Rankine states, and are discussed thoroughly by Lambe and Whitman (1969) and in other soil mechanics texts.

For the simplest case of a cohesionless granular material retained by a frictionless wall, k_a is the ratio of horizontal to vertical active pressure, p_h/p_v . The active horizontal pressure so determined is the minimum pressure, since the full shear stress of the solids is mobilized. For the active state of stress to apply, the retaining wall must deflect away from the solids an amount in excess of about 0.001 to 0.004 times the height of material at the wall. If the wall does not deflect this amount, the pressure can be significantly higher, approaching the value for the wall at rest. The largest pressure results for the passive state of stress, since both the full shear stress of the solids and the force of gravity acts to resist the applied thrust of the wall. Ignoring the differences between the internal friction angle for the active and passive stress states and assuming cohesionless granular solids, $k_p = 1/k_a$.

The analysis of Rankine (Lambe and Whitman) led to the relationship:

$$\begin{aligned} k_a &= \frac{1 - \sin \phi}{1 + \sin \phi} \\ &= \tan^2 (45 - \phi/2) \end{aligned}$$

where ϕ is the friction angle or angle of shearing resistance. The friction angle may be determined from a plot of the Mohr failure envelope on a standard Mohr diagram of shear stress versus normal stress for the material. The slope of the Mohr failure envelope is equal to $\tan \phi$. Usually, this Mohr envelope is a curved line due to the cohesiveness of the solids, and the slope must be estimated by drawing a straight line through the data points and passing through a non-zero value of shear stress at zero normal stress called the cohesion intercept.

The values of the coefficient of stress for active and at-rest stress states for a range of internal friction angles are illustrated in

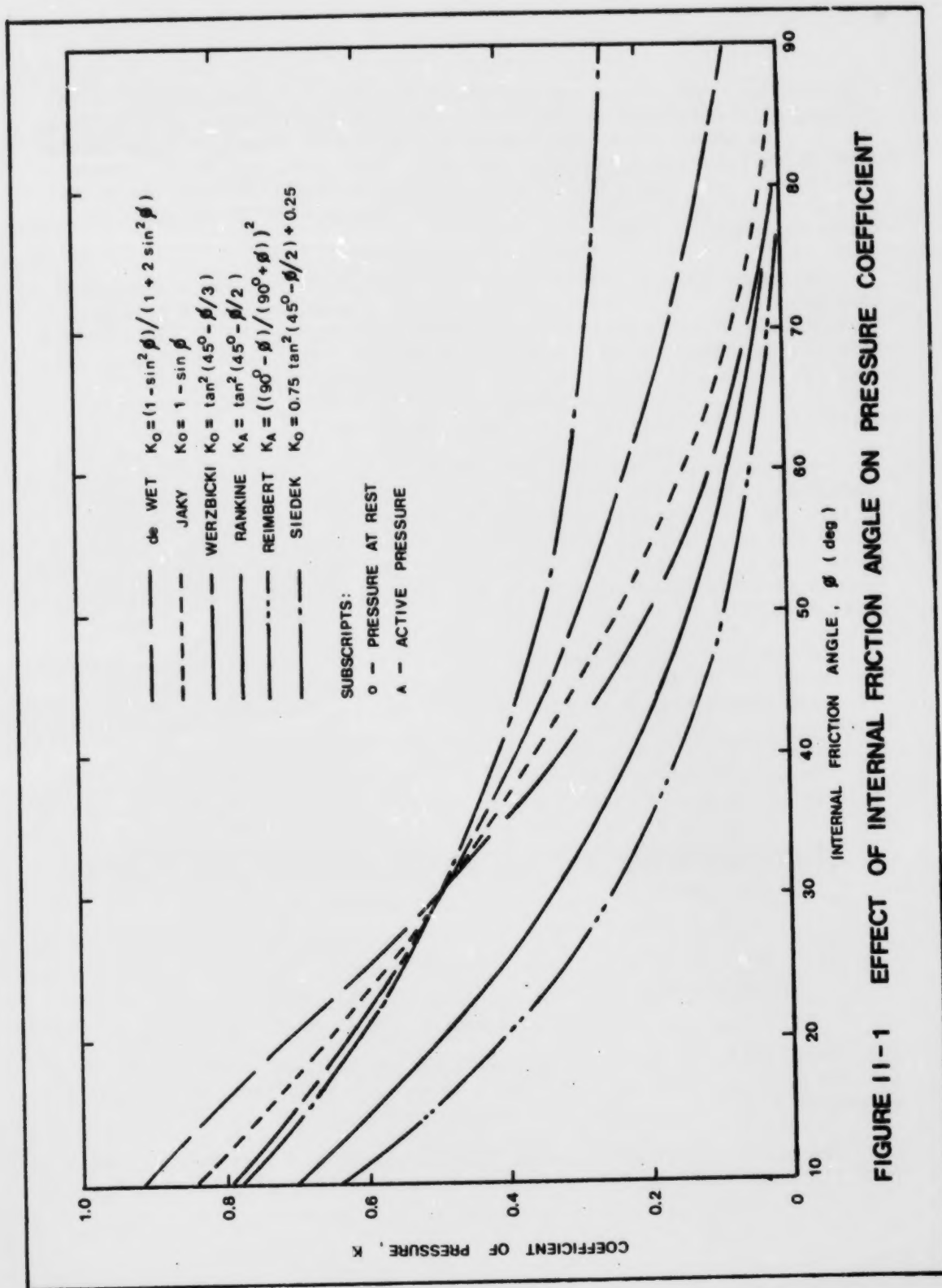


FIGURE 11-1 EFFECT OF INTERNAL FRICTION ANGLE ON PRESSURE COEFFICIENT

Figure II-1. The stress coefficients all apply to cohesionless solids against a frictionless vertical wall and with a horizontal pile surface. The results shown for Reimbert were determined by extensive experimentation using laboratory equipment and are, therefore, empirical. These experiments have shown that the wall-friction coefficient has no effect on the thrust imposed on the wall. This is contrary to the approach taken by others for theoretical analysis.

Of importance in this plot is the range of values for k that have been proposed. All relationships indicate the well-accepted behaviour that the coefficient of stress increases with decreasing ϕ . To ensure a safe design under conditions of active thrust, the fairly standard practice is to use the lowest value of ϕ for the material, which is the natural angle of repose. This approach maximizes k_a and, therefore, maximizes the estimate for the thrust on the wall.

Internal friction angles are difficult to estimate for in-field conditions, since they depend not only on the size, shape, and other factors for the material itself, but also on the conditions present within the pile such as voidage and local confining pressure. The particle size of the solids is particularly important, since irregular or fibrous particles such as are present in wood residues tend to interlock, resulting in an increase in ϕ .

The angle of repose measured for wood residues in this study varied from about 30° to 40° . With these values for ϕ , the active stress coefficient ranges from 0.16 to 0.34 based on results given in Figure II-1.

The active thrust developed on a retaining wall with wall friction is at an angle to the surface of the wall as shown in Figure II-2. This angle, θ , is equal to the arctangent of the friction coefficient. The theoretical solution to the problem of a retaining wall supporting cohesionless granular solids was derived by Coulomb (Lambe and Whitman) to be, $P_a = k_a \gamma H$ where:

$$k_a = \frac{\sin^2(\alpha + \phi)}{\sin^2 \alpha \sin(\alpha - \theta) \left[1 + \frac{\sin(\phi + \theta) \sin(\phi - \beta)}{\sqrt{\sin(\alpha - \theta) \sin(\alpha + \beta)}} \right]^2}$$

The resultant force from this pressure acting over the area of the retaining wall is shown as P in Figure II-2. The resultant, P , acts at a height of $H/3$.

The above relationship gives total pressure and must be resolved into its components to determine the imposed horizontal pressure, P_{ah} .

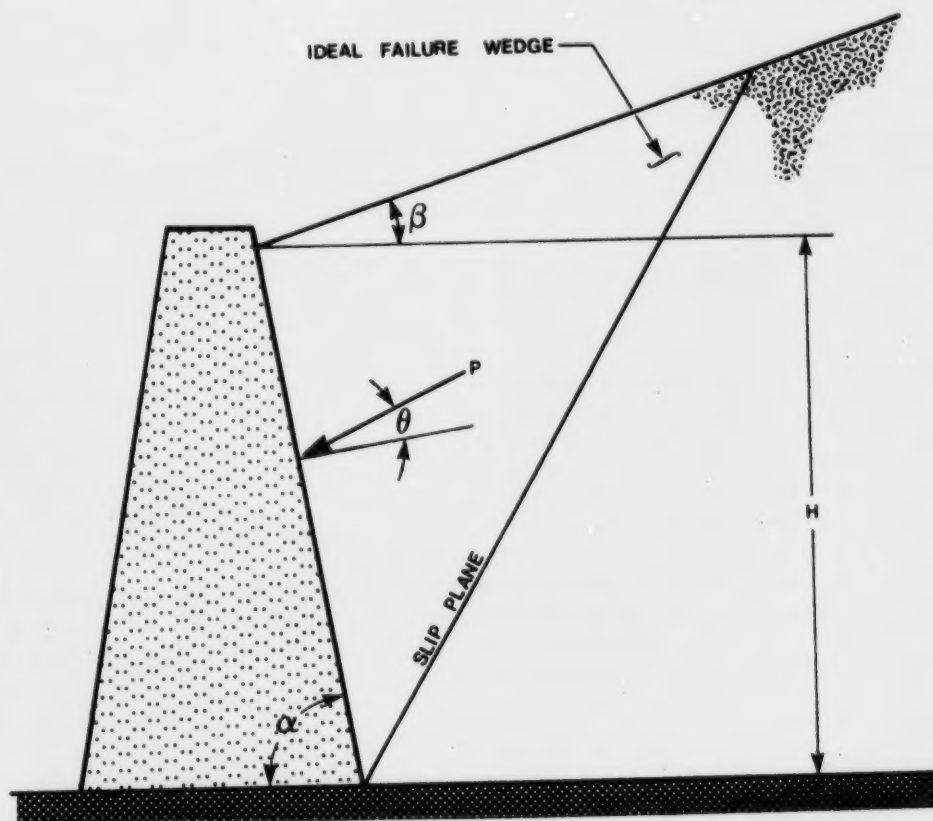


FIGURE 11-2 VARIABLES USED IN THE COULOMB
EQUATION FOR PRESSURE ON
RETAINING WALL

Considering the case of a vertical wall ($\alpha = 90^\circ$), the equation becomes:

$$P_{ah} = \frac{\gamma H \cos \theta \cos^2 \phi}{\cos \theta \left[1 + \sqrt{\frac{\sin(\phi + \theta) \sin(\phi - \beta)}{\cos \theta \cos \beta}} \right]^2}$$

$$= k_a \cos \theta \gamma H.$$

Denoting the horizontal active pressure coefficient as k_{ah} , the relationship may be written as $P_{ah} = k_{ah} \gamma H$ where:

$$k_{ah} = \frac{\cos^2 \phi}{\left[1 + \sqrt{\frac{\sin(\phi + \theta) \sin(\phi - \beta)}{\cos \theta \cos \beta}} \right]^2}$$

Values of k_{ah} for various values of ϕ and at values of β and θ near what was measured during the field tests are given in Figure II-3. When the pile is flat, k_{ah} varies from 0.26 to 0.18 as ϕ increases from 30° to 40° . These values are very close to values predicted by Reimbert, but are lower than values predicted by Rankine. The relationship is relatively insensitive to the wall friction angle.

The load imposed on a vertical retaining wall can be calculated by integrating the pressure relationship over the area of the wall. For a linear pressure distribution over the height of the wall the integration is straight forward giving the relationship:

$$P_{ah} = \gamma \frac{H^2}{2} k_{ah}$$

This load acts at a height of $H/3$.

The pressure imposed on the wall can be normalized with respect to bulk density to enable comparison of data on equivalent basis. The value of P_{ah}/γ is then solely a function of H and k_{ah} . This approach is used in Chapter V to present the test data. k_{ah} is a function of the internal friction angle, the wall friction angle, and the angle of the pile surface. In practice, k_{ah} also depends on the height and shape of the pile, making its value fairly case specific. In field studies Wroth (1972) has observed that k_0 decreases in a logarithmic fashion with increasing depth asymptotically approaching a constant value. Symons and Wilson (1972) have observed for pulverized fuel ash piled behind a retaining wall that k_{ah} decreased with increasing depth, and the pressure distribution on the wall was not linear.

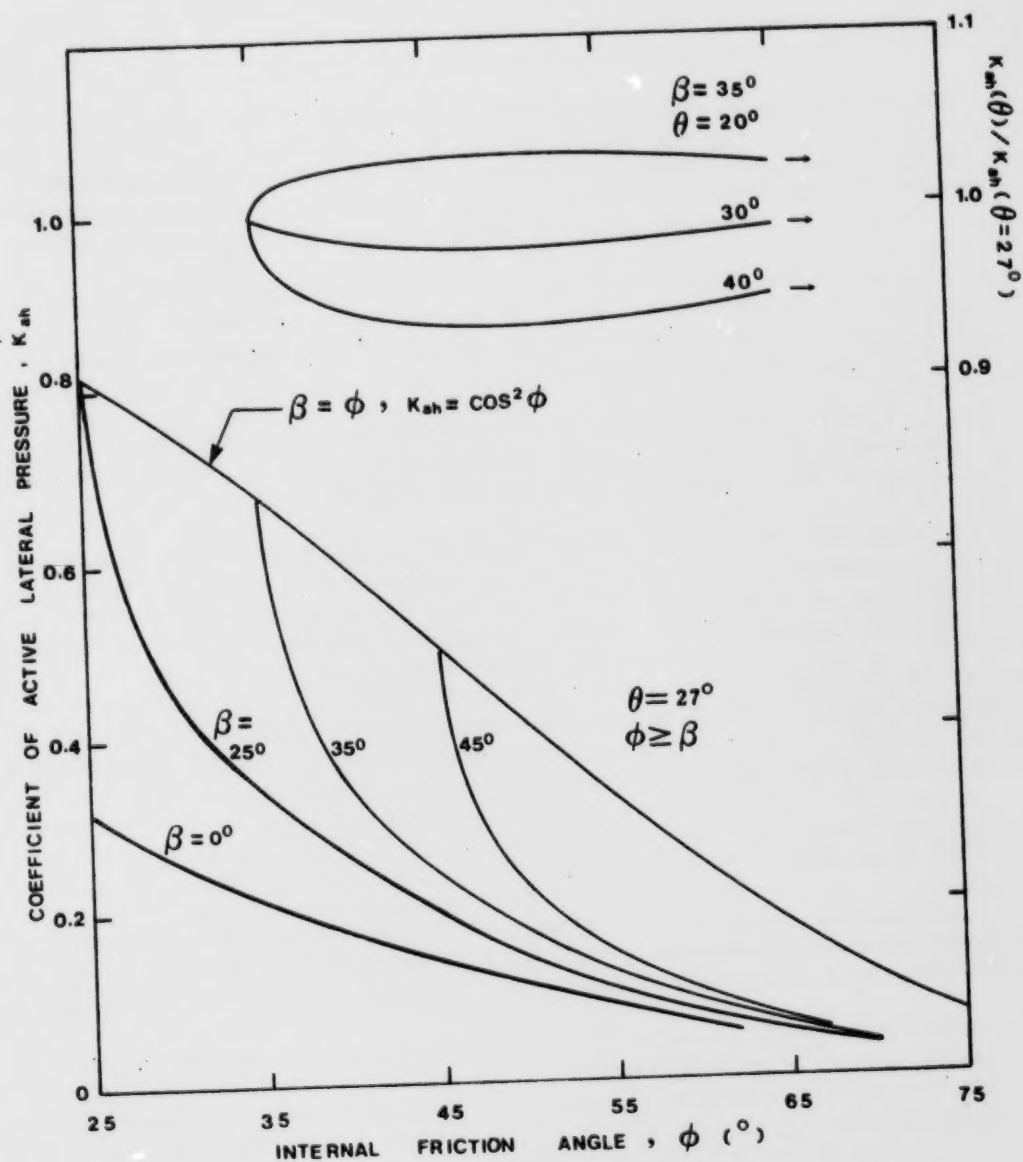


FIGURE 11-3 THEORETICAL VALUES OF K_{ah} AT VARIOUS VALUES OF ϕ , β AND θ

III. PHASE I TESTS

A. Objectives

The objectives of Phase I of the study were:

- to select commercially available instruments and, if necessary, to develop new instrumentation for measuring the lateral pressure imposed by hog fuel or other wood residues on a retaining wall;
- to apply the most promising candidate instruments under ordinary plant operating conditions, to assess their performance and suitability, and enable the selection of the design suitable for data acquisition in Phase II;
- to identify the parameters influencing the pressure imposed by a hog fuel pile and monitor lateral pressure developed as a function of pile shape and depth at the bottom of the pile.

Phase I concentrated on the selection and design of instrumentation and the development of a test procedure that would be used in Phase II to gather most of the pressure data for the loading conditions within the scope of this study. A limited number of test runs were conducted in Phase I to gather pressure data as a function of pile height. Samples of hog fuel being used in the tests were collected and characterized by density, moisture content, and particle size. The internal friction angle of the material after screening to suit laboratory equipment was also determined.

B. Test Site Description

A survey of potential mill sites for the project in the Greater Vancouver area was conducted. From this survey, it was decided to conduct the Phase I testing at:

Crown Zellerbach
Coast Wood Products Division
15 King Edward Avenue
Coquitlam, B.C.

and the Phase II testing at:

Canadian Forest Products Ltd.
Plywood and Hardboard Division
440 Canfor Avenue
New Westminster, B.C.

These mills offered sites compatible with the planned test programs and which could be altered to install the required instrumentation.

The Crown Zellerbach mill (Fraser Mills) made available a storage and mixing bin in which hog fuel is handled for delivery to a steam plant. The hog fuel is confined between near vertical wooden walls and is built-up during the week and drawn-down during the weekend.

The storage bin (Figure III-1) is a timber building built in the 1920's measuring approximately 46 m (150 feet) long by 12 m (40 feet) wide by 21 m (70 feet) high. The bin wall is constructed of 25 cm X 25 cm vertical timber columns at about 3 m spacing. The timber columns form the outer frame and support a 15 cm thick wooden wall made of 5 cm X 15 cm lumber nailed together. The bottom of the bin is about 2 m above ground.

The bin is divided into two sections. The smaller section (15 m long) is used to store dry material while the larger section, (31 m long) where the test was done, is used to mix and store wood residues produced at the sawmill, planer mill, and debarker. The mill's operations dictate the rate of generation of the wood residues. There is essentially no control of the incoming rate of material or the proportions of the types of residues, since these rates are subject to independent mill operations. The hog fuel is reclaimed constantly by two flight conveyors below floor level and used as fuel in the steam boiler and, therefore, the reclaiming rate depends on steam demand. The hog fuel stored in the bin is used to fuel the boiler over the weekend when residue-producing parts of the mill are shut down.

Incoming hog fuel is transported by an overhead conveyor running along the bin at its center (Figure III-2). The hog fuel is discharged into the bin through manually controlled slide gates with deflector chutes located at fairly regular intervals along the bin: 8, 11, 14, 17 m. A hydraulic rake operates inside the bin to draw-down the stock pile which bridges across the openings to the reclaiming conveyors. This rake is monitored and controlled from the boiler room. The rake travels along the bin on a rail located directly under the overhead conveyor, however, the design is such that a dormant pile of material normally remains against the wall after the bin has been emptied.

During the week, the pile is built-up from one end to the other (left to right in Figure III-2) in the direction toward the hydraulic rake. The pile is drawn-down in the reverse direction during the weekend. The bin fills to 21 m from the dividing wall by Friday night and empties to about 3 m by Sunday evening. The full height of the pile is about 6 m at the side walls with the peak reaching the infeed chute.

In summary, the Fraser Mills test site had the following attributes:

- the material handled was hogged for use as boiler fuel;
- the filling and emptying operations of the bin were repeated in a reasonably short period of time (7 days).

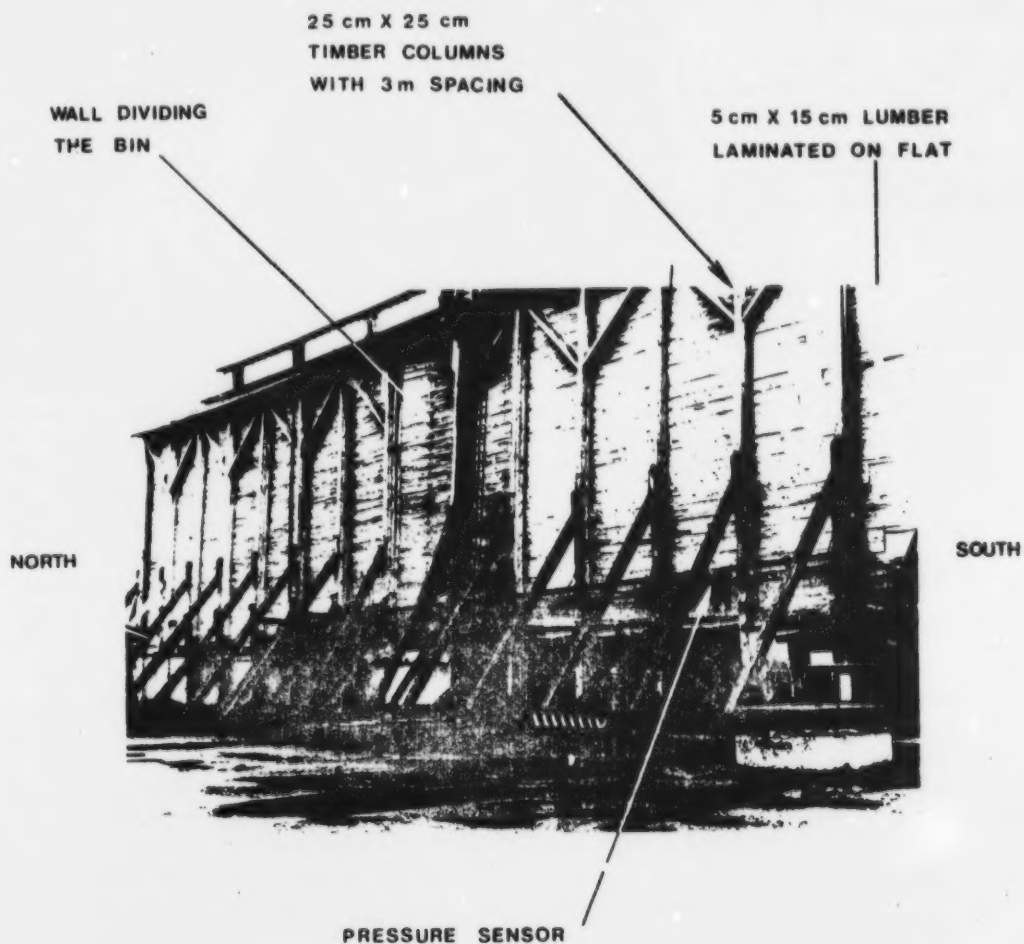
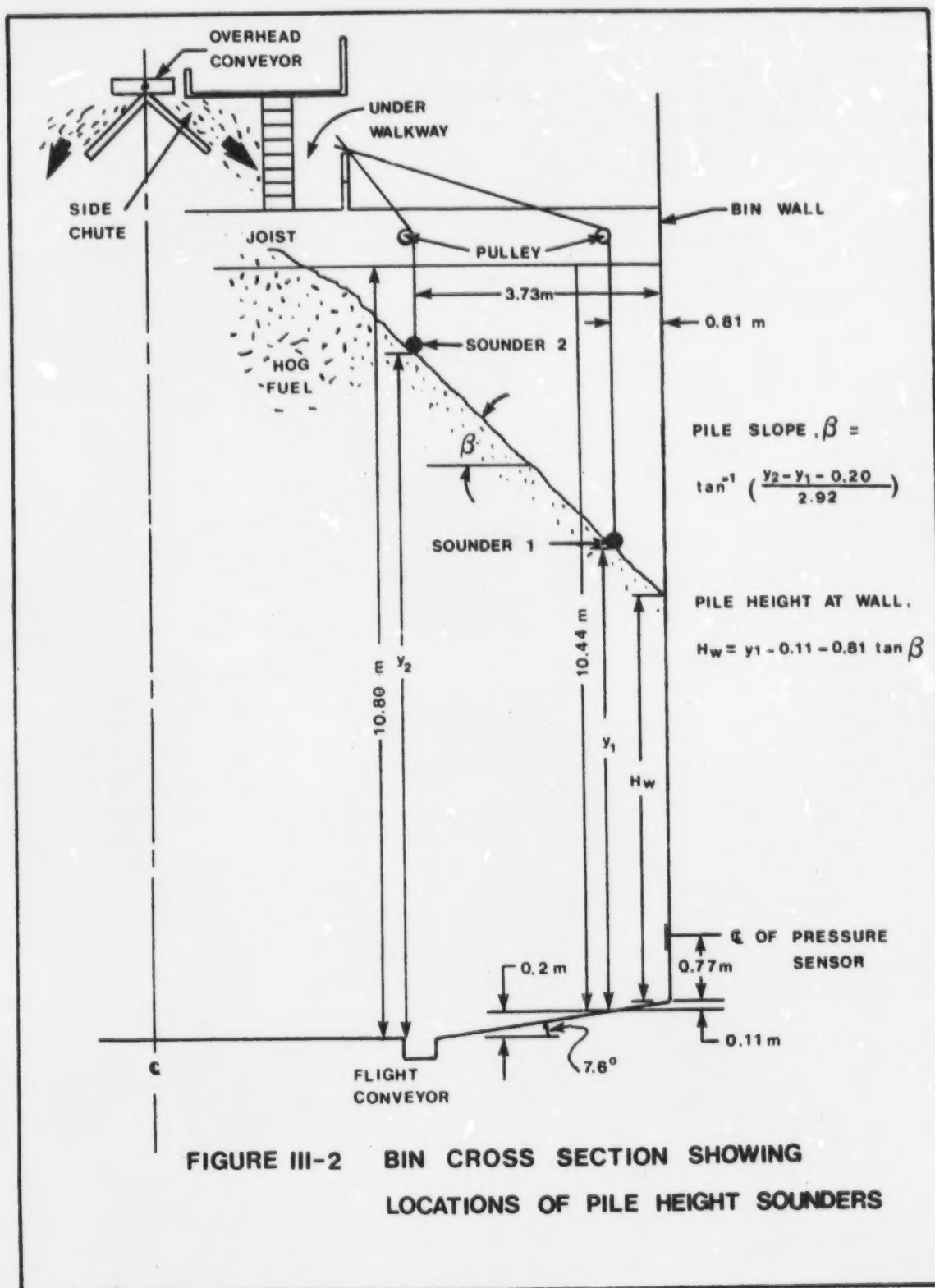


**FIGURE III-1 CROWN ZELLERBACH (FRASER MILLS)
TEST SITE**



- the method of loading was by gravity, resulting in natural compaction of the material only;
- the pile height was typical for wood residues (6 m);
- inside storage minimized changes of material characteristics to be monitored: moisture content, density, and particle size.

C. Design and Calibration of Pressure Sensors

The pressure sensors for measuring lateral pressure exerted by hog fuel were selected and/or designed based on the following criteria:

- the sensors had to have a low profile when mounted on a bin wall to minimize any disturbance of the normal pressure distribution on the wall, and to avoid local anomalies such as bridging of material across part or all of the sensor;
- the displacement under loading must be near zero to avoid any or most pressure relaxation and consequent measurement error;
- the sensor output should be suitable for automatic recording.

A survey of commercial pressure-sensing equipment was conducted to ascertain whether equipment suitable for the test program was presently marketed. This survey led to the identification of a piezometric cell as the only suitable commercial design. Several alternative conceptual designs were also investigated due to doubts about the effectiveness of the commercial 19.4 cm diameter piezometric cell when measuring pressures imposed by residues having pieces sized upwards of 10 cm. Bridging across this sensor was perceived as a potential problem. The design selected as an alternative to the piezometric cell was a nominal 28 cm high by 61 cm long by 0.6 cm thick steel panel mounted flush with the wall, hinged at its upper edge, and supported by two cells at its lower edge. The size of the sensing surface was selected to reduce pressure measurement errors due to bridging of particles between the wall and sensor surface and yet give a representative value for the local pressure.

1. Load Panel System

The load panel system (Figure III-3) was made of stainless steel to avoid corrosion, supported with common hinges at its upper edge and restrained at the bottom with two low-displacement load cells.

The selected load cells (Appendix I) are electromechanical devices that produce an electrical (voltage) output signal in proportion to an applied load (Figure III-4). Knowing the locations of the load cells on the panel, the voltage outputs of the two load

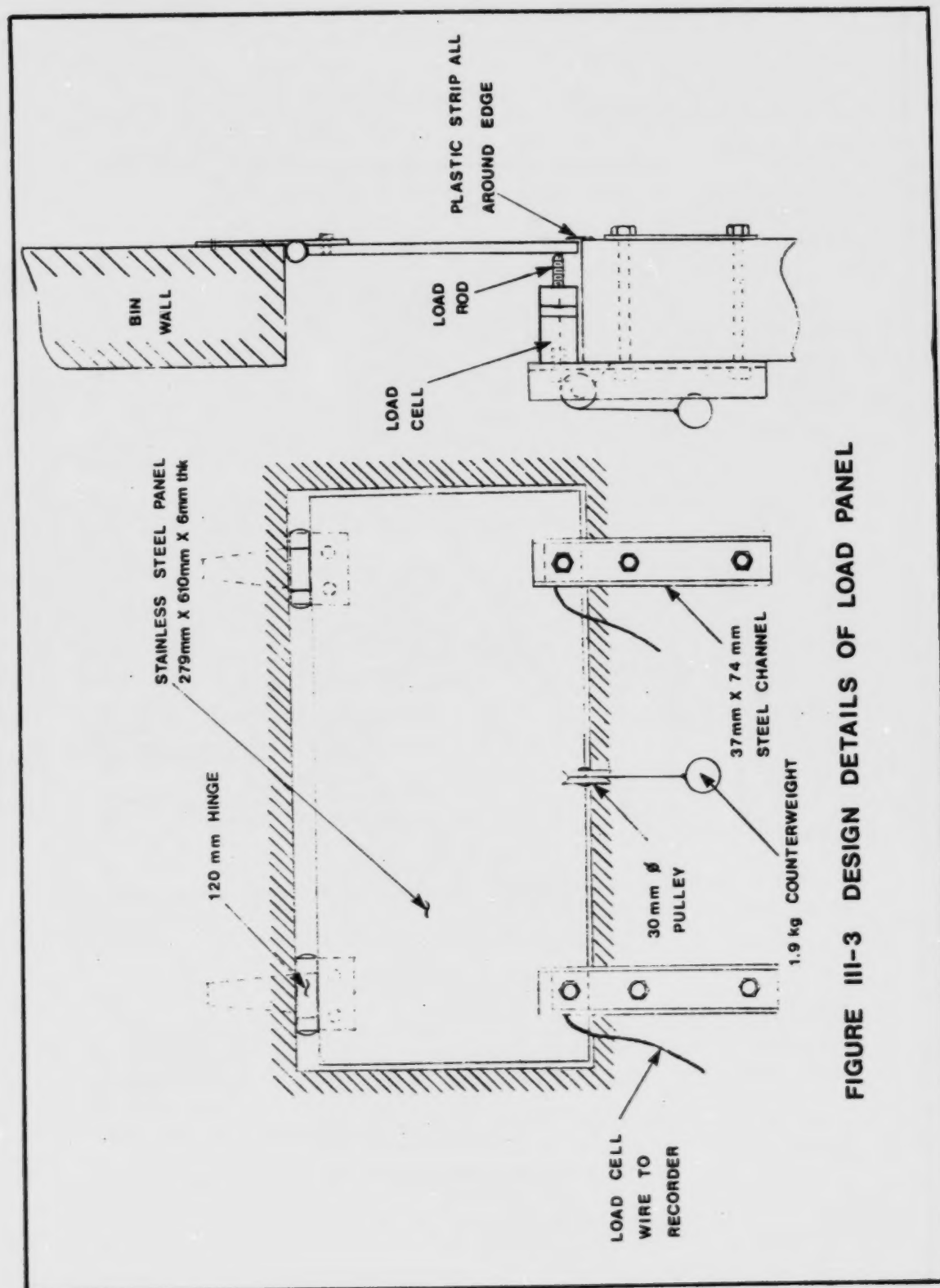


FIGURE III-3 DESIGN DETAILS OF LOAD PANEL

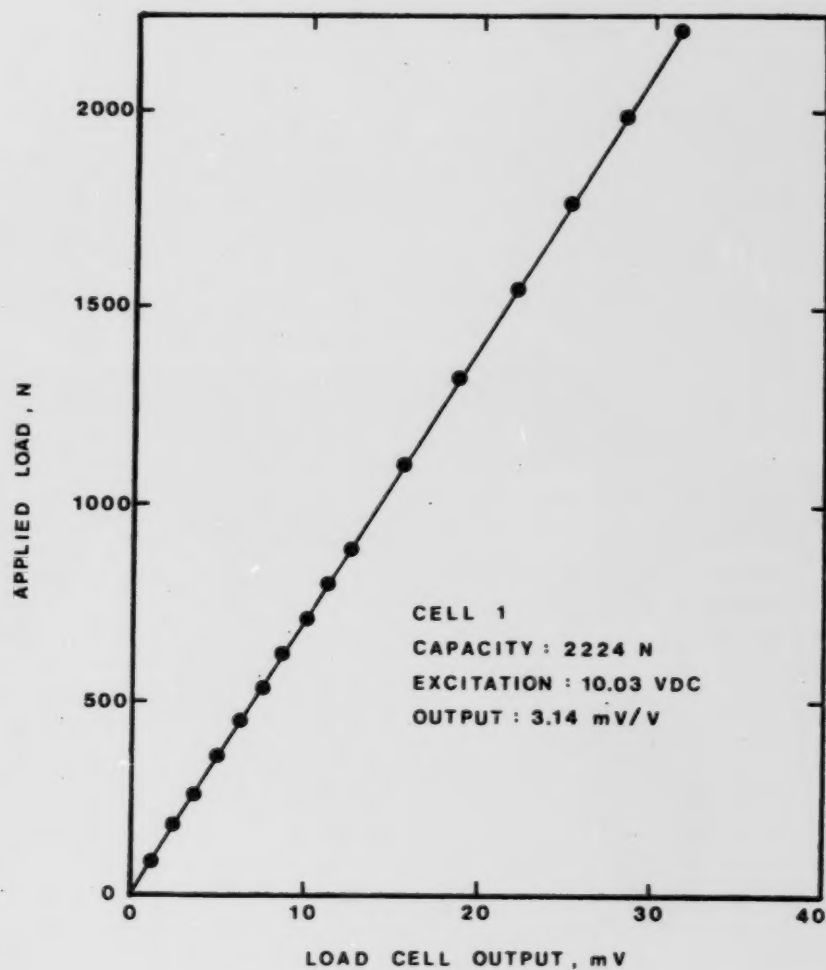


FIGURE III-4 TYPICAL LOAD CELL RESPONSE

cells were related to the imposed lateral pressure using a simple equation for the static movements about the two aligned hinges (Appendix II).

Due to the uncertainty of the maximum pressure that would apply to the panel, two high capacity (2,224 N) load cells were used initially. After the maximum pressure had been determined in the first two runs of the test, these were replaced by two 1,112 N load cells in order to improve the sensitivity.

With two 2,224 N load cells, the maximum capacity of the system is 44.6 kPa with a sensitivity of 0.15 kPa based on load cell specifications. With two 1,112 N load cells, the maximum capacity of the system is 22.2 kPa with a sensitivity of 0.07 kPa. The deflection of the system is less than 0.2 mm at maximum loading using either pair of load cells.

For Phase I, the load panel was installed as shown previously in Figure III-3 such that the sensing surface was approximately flush with the wall surface. The load cell supports were oversized channel-iron to minimize deflection. Flexible plastic strip was placed around the edge of the panel to avoid problems with jamming and spillage of the residues. A single centrally-mounted counterweight was attached to eliminate clearances between moving parts and to enable in-field calibration of the panel system.

All load cells were calibrated at B.H. Levelton & Associates Ltd. using a Baldwin Universal Testing Machine.

After installation of the load panel for Phase I, it was calibrated by monitoring output response during incremental weight changes to the counterweight (Figure III-5). The deviation between the actual and the ideal response of the load cells is due to frictioned torque developed by the hinges and to small dimension errors. The deviation factor was incorporated in the final calibration equation for the sensor (Appendix II).

2. Piezometric Pressure (Pancake) Cell

The piezometric (pancake) cell is a commercially available item manufactured by Petur Instruments Ltd. in Port Coquitlam, B.C. It is designed to measure the pressure acting on a plane surface, its main application being in the field of soil mechanics. The system (Figure III-6) consists of a thin circular (pancake) cell filled with an incompressible fluid (glycol), a piezometer, and a control box for pressure read-out and air supply.

The pancake cell is made from two stainless steel plates welded together at the edge leaving approximately a 1 mm space which is filled with glycol or some other incompressible fluid. The cell is 10 mm thick with an active loading area of 295 cm². It is

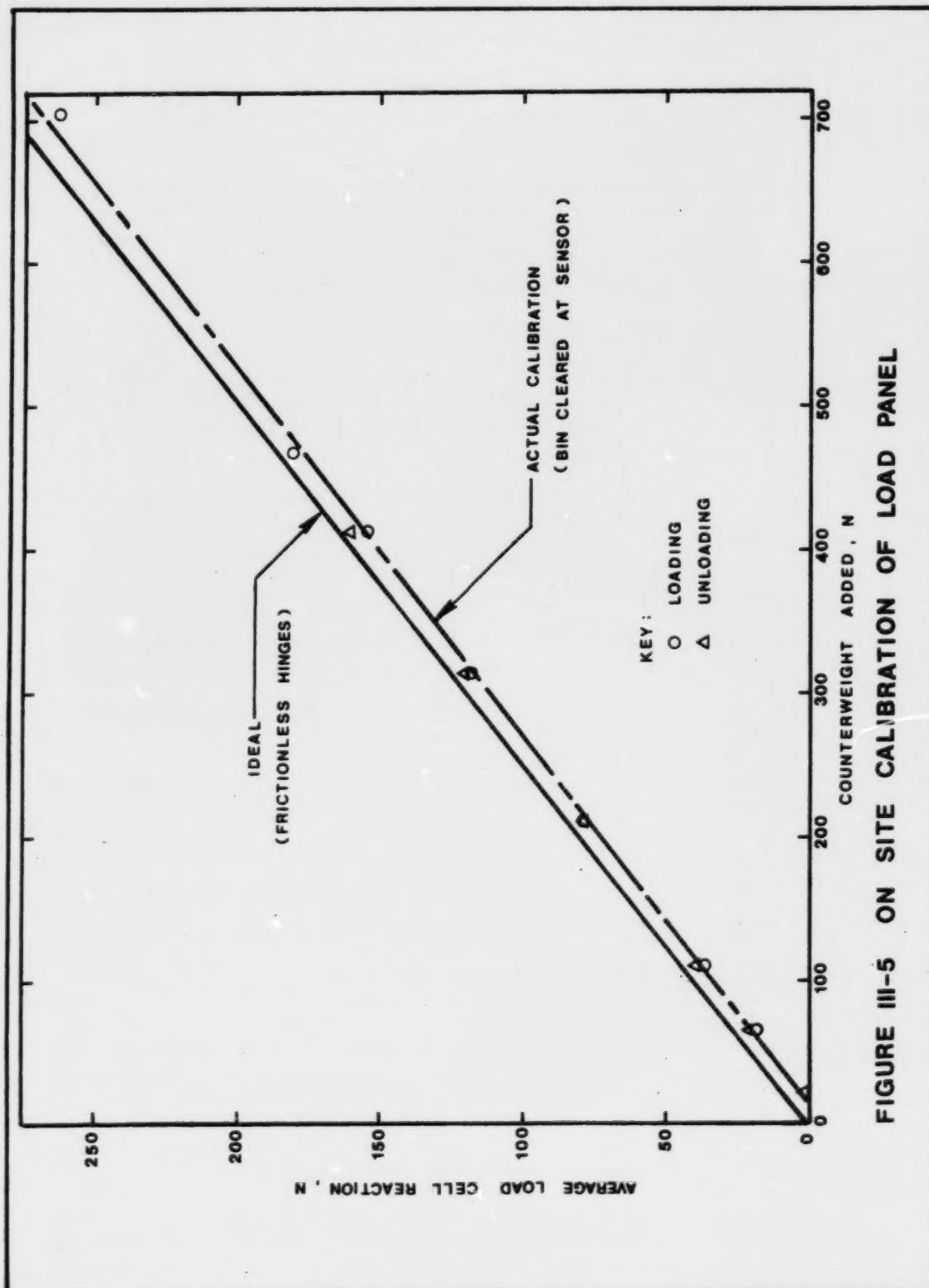
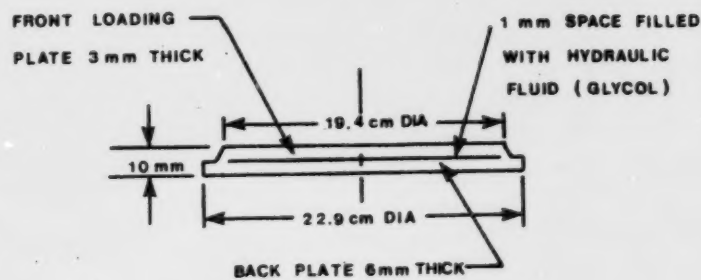
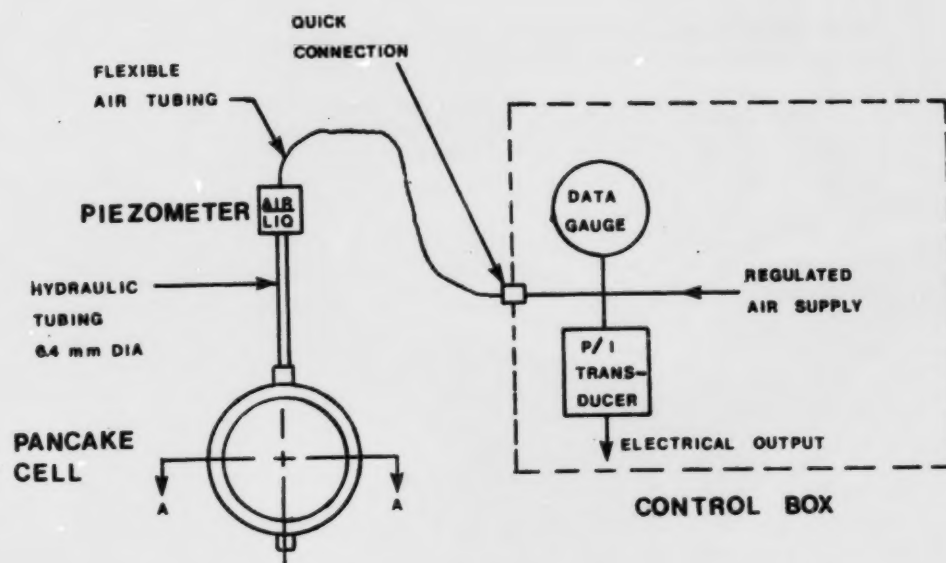


FIGURE III-5 ON SITE CALIBRATION OF LOAD PANEL



SECTION A-A

**FIGURE III-6 LAYOUT OF PIEZOMETRIC
PRESSURE (PANCAKE) CELL**

connected to the piezometer with a stainless steel hydraulic tube 6.4 mm in diameter and of arbitrary length.

The pressure imposed on the pancake cell is transmitted to the pneumatic line through a piezometer (1:1 pressure ratio) and subsequently, to a Bourdon gauge in the control box.

The control box supplies and regulates the air flow to the piezometer and houses a Bourdon gauge. During the test, a pressure-to-current (P/I) transducer was added in parallel to the Bourdon gauge such that the system output could be recorded automatically. The system, excluding the P/I transducer, was calibrated by the supplier before delivery. The range and accuracy of the Bourdon gauge readout was 103 kPa and ± 0.3 kPa, respectively.

The pancake cell was mounted at the center of a piece of plywood 76 cm X 76 cm X 13 mm thick (Figure III-7) with the sensing surface about 4 mm above the surface of the plywood. The plywood was nailed onto the wall adjacent to the load panel. The piezometer of the pancake cell passed through the hole behind the load panel for mounting outside.

After the pancake cell was installed at the test site, it was calibrated with the P/I transducer readout by manually applying pressure to the cell while monitoring the P/I transducer and pressure gauge readouts. The P/I transducer output varied linearly with applied pressure as shown in Figure III-8.

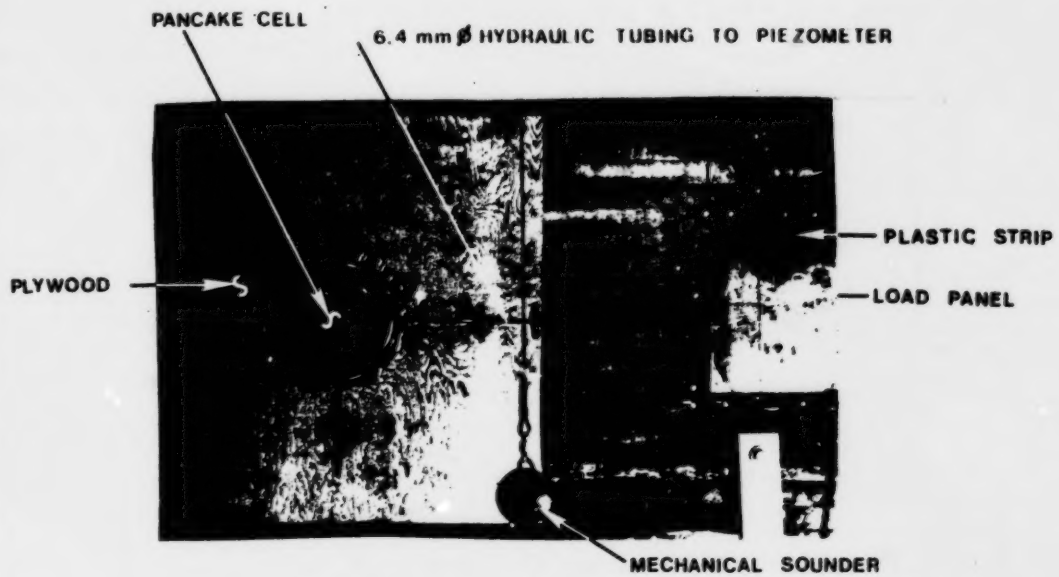
D. Data Measurements and Procedures

The experimental work of Phase I was carried out at Fraser Mills starting the week of November 15 and ending the week of December 14, 1981. During the six weeks, four sets of data were collected. Each set of data includes the pressure at the sensor location, the pile height at three locations, the deflection of the retaining wall near the pressure sensor, and the physical characteristics of the material.

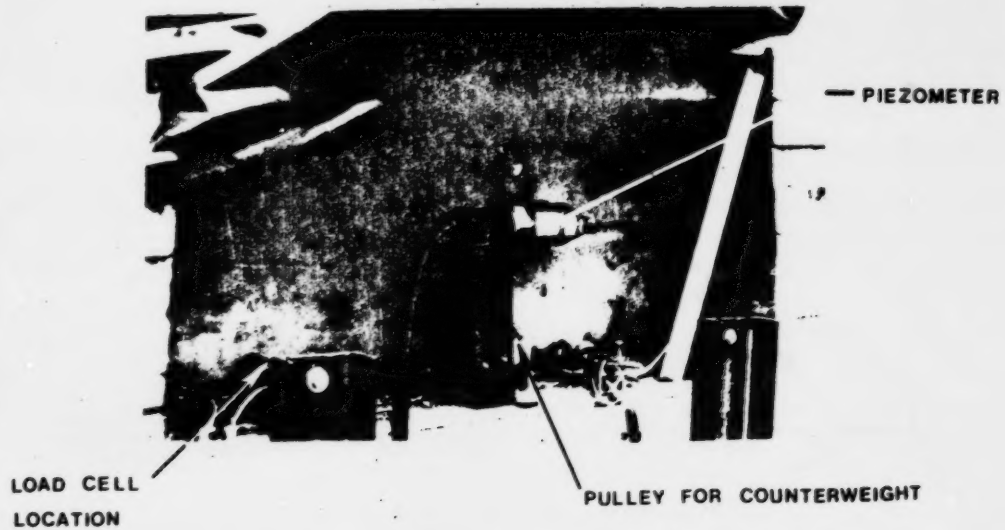
1. Mill Operating Schedule

The mills which generated all the wood residues forming the test pile normally operated three shifts a day Monday through Friday. The steam plant operated twenty-four hours a day, seven days a week. Wood residues produced by the mills were constantly transported to the bin, reclaimed, and fed to the boilers. Any surplus fuel was stored in the fuel bin for the weekend.

During the first two weeks of testing, the mills operated three shifts per day, causing the bin to fill steadily during the week. Subsequently, the mills were shut down for the graveyard



A. PRESSURE SENSORS ON WALL



B. PIEZOMETER AND LOAD CELLS

FIGURE III-7 MOUNTING OF PANCAKE CELL
AND LOAD PANEL

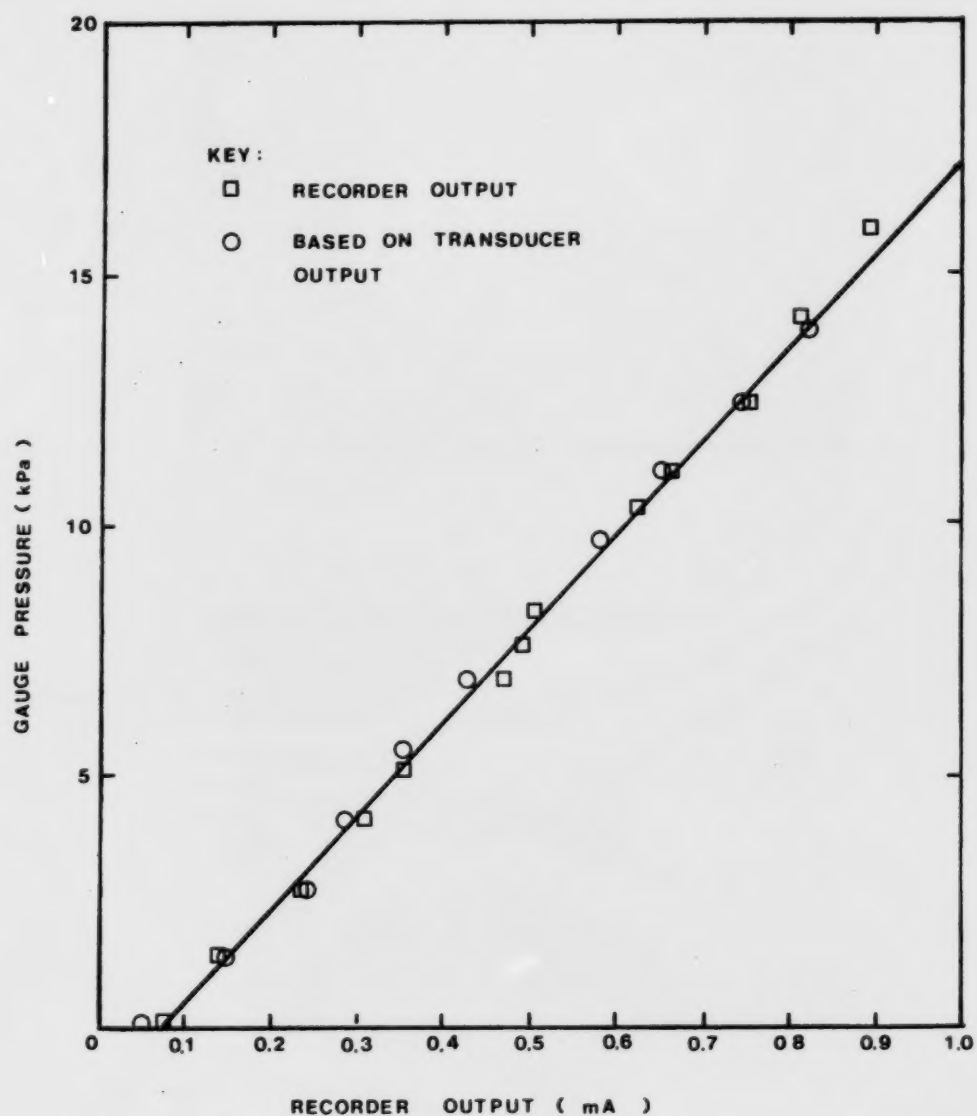


FIGURE III-8 CALIBRATION OF P/I TRANSDUCER
AND RECORDER

shift causing the bin to fill during the day and afternoon shifts, and to empty during the graveyard shift.

The natural variability of the infeed and outfeed rates with process demands and manning schedules often made control of the pile build-up at the location of the pressure sensor a difficult task, since the mill operation could not be altered. The tests in Phase I were conducted in coordination with the mill operation, resulting in data for each run that were unique in some way. Repeat runs under very similar loading conditions and with similar feeds could not be done without undue alteration of the mill operation, although this does not in any way detract from the results obtained.

2. Pressure Measurements

The load panel and the pancake cell were installed after the dormant material was cleared away from the wall for a width of about 3 m. The two sensors were installed 0.77 m above the floor to the center line, 11 m from the north end of the bin and under the second discharge chute. The first discharge chute was located at the 8 m section.

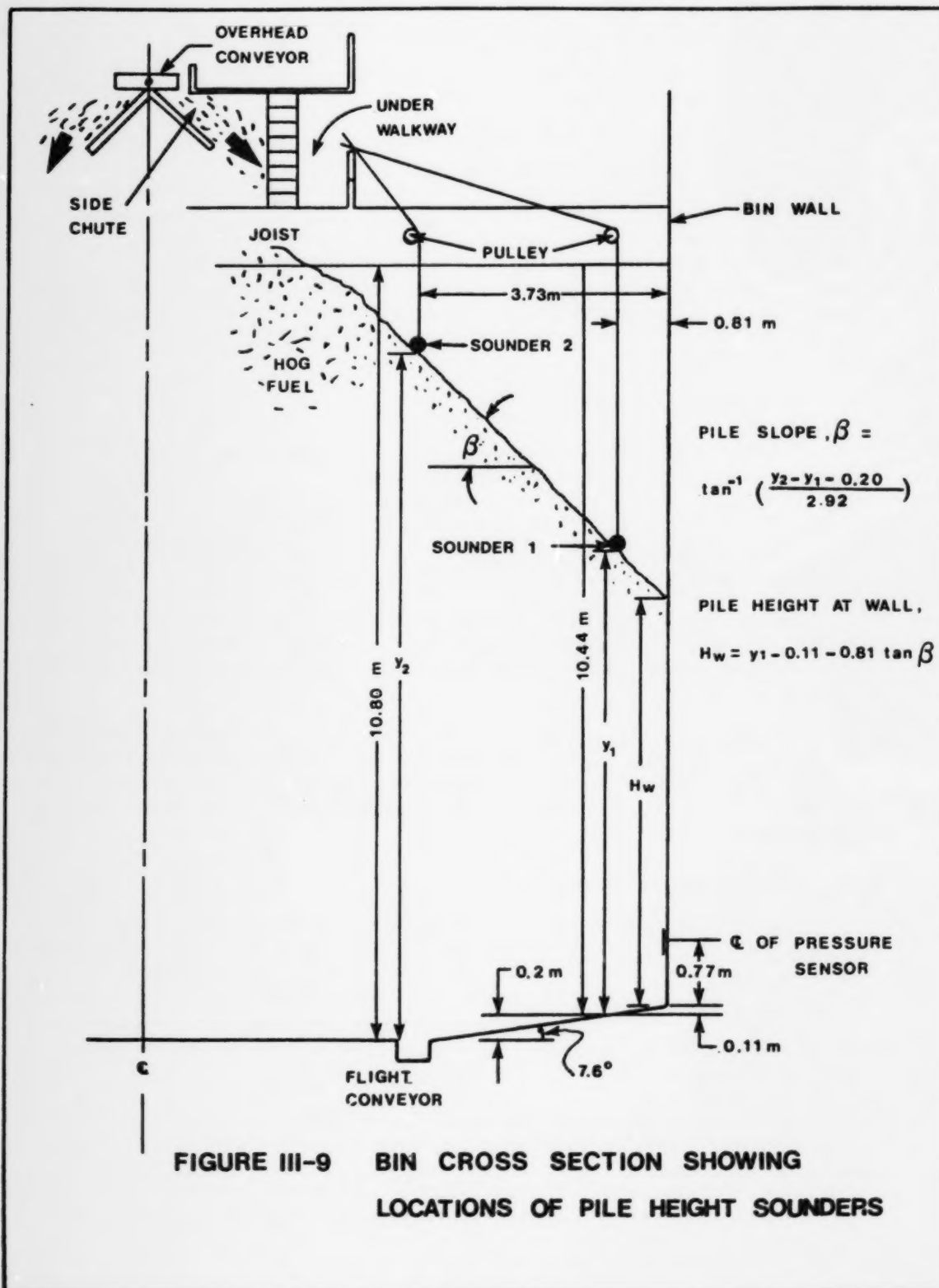
Under normal operation, the 11 m section would start filling on Tuesday morning at about 0800 hour and would continue filling for about ten hours, after which the chute located at 14 m would be opened.

The electrical outputs of the two sensors were recorded continuously on two strip-chart recorders. The outputs were checked regularly with a multimeter to ensure the recorders were registering correctly. The electrical outputs were converted to equivalent pressures after the test.

3. Pile Height Measurements

The pile heights were manually measured with two mechanical sounders which were installed on the joist of the fuel bin directly over the two pressure sensors at known distances from the wall (Figure III-9). By simple trigonometry, the pile height at the wall, as well as the slope of the pile, was calculated. A 3.66 m scale was mounted on the wall at a height of 3.09 m, directly above the pressure sensors, after the second run of tests.

Until the pile reached the wall scale, the pile heights at the wall were estimated by extrapolating from the pile heights measured by Sounders 1 and 2. Subsequently, pile heights at the wall were measured using the wall scale. With the sounding devices, the pile height measurements were within about ± 5 cm.



The pile heights were manually measured and recorded regularly at 10 minute intervals when hog fuel was filling the section of the bin in front of the pressure sensors. Height measurements halted once the flow of feed onto the pile above the sensors had ceased, and the next infeed chute was opened. The final height measurement was taken the following Friday when the bin was nearly full.

The hog fuel pile was drawn-down with the aid of the hydraulic rake during the weekend. The hydraulic rake interfered with the two sounders, and therefore, pile heights could not be measured during draw-down of the pile.

4. Wall Deflection

The deflection of the bin wall was measured at the following three locations:

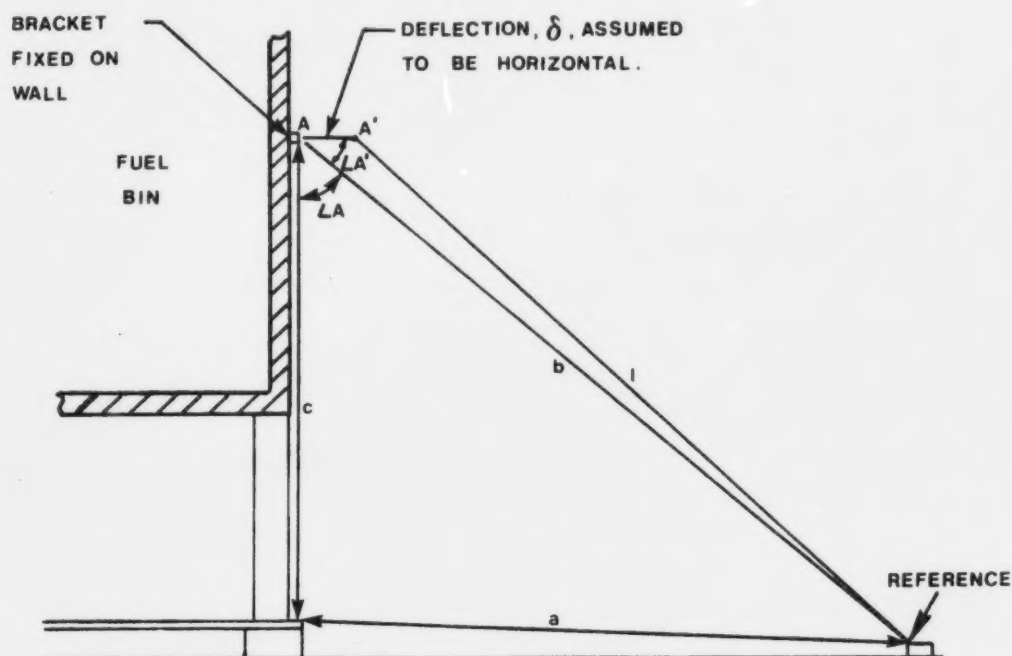
- panel - 41 cm above the center of load panel;
- mid-span - center of the wall section where the two sensors were located, 51.4 cm above the center of the load panel;
- post - on the timber column between the 11 m and 14 m sections of the bin, at 33 cm above the center of the load panel.

The method used to estimate the deflection of the bin wall is illustrated in Figure III-10. The deflection, δ , of the bin was calculated from the measured length, l , using a developed relationship (Appendix III) which assumes wall deflection is horizontal.

The wall measurement method was chosen to give mostly qualitative data concerning the flexibility of the wall. These data are needed to determine whether the recorded pressures apply to the active or at-rest pressure regimes.

5. Material Characteristics

Wood residues from the mill operations were fed to the bin relatively unmixed, resulting in a fuel pile that was in no way uniform or homogeneous. To obtain a representative sample for characterization, three samples having a combined weight of about 30 kg were collected in plastic bags from the overhead discharge chute at various times during a test run. These samples were returned to the laboratory sealed, mixed thoroughly, then split to obtain a sample for determination of bulk density, moisture content, and size distribution. A limited number of tests were done to determine the flow properties of hog fuel.



$$\text{DEFLECTION, } \delta = b \cos (\angle A') - \sqrt{b^2 \cos^2 (\angle A') - (b^2 - l^2)}$$

FIGURE III-10 METHOD USED TO DETERMINE BIN WALL
DEFLECTION AT FRASER MILLS FOR
PHASE I

a) Bulk Density

The bulk density of the hog fuel was determined using the mixed sample, as received, by placing the sample in a nominal 30 cm X 30 cm X 30 cm container. The sample volume was determined in the loose condition immediately after filling and after packing by dropping it five times from a height of 15 cm onto a nonresilient surface. Bulk densities given in this report apply to the samples in the packed condition.

b) Moisture Content

A sample of about 1 kg, as received, was dried in a ventilated oven at 110°C for twenty-four hours or until no further weight loss was observed. Moisture contents are reported on a wet basis.

c) Size Distribution

The size distribution of the hog fuel was determined by passing a 0.5 kg sample of dry material through a standard set of metric sieves.

d) Flow Characteristics.

A sample collected on November 27 was tested at B.C. Research to determine the wall friction angle, internal friction angle, and shear strength of the material. Due to limitations of this testing apparatus, the wall friction and internal friction angles were determined with the portion of the sample passing a 2.5 cm screen. Consequently, the determined values may not apply to the residues sampled from the bin.

The apparatus and test procedures for determination of flow properties of wood residues were developed as part of ENFOR Project C-130, "Bin and Silo Design for Biomass Materials", being conducted by B.C. Research, Vancouver. Bundalli and Morgan (1981) have previously described the flow test equipment and test procedure.

E. Test Results

Four sets of data were collected during Phase I at Fraser Mills. The following discussion presents the data obtained during these tests and a description of the test conditions. Correlation and interpretation of the data from Phase I and Phase II are dealt with in Chapter V.

1. Run 1 - November 16 - 17

Prior to Run 1, the residues remaining against the wall for about a 0.6 m distance on either side of the two pressure sensors were removed to ensure the measured pressures applied to a freely-formed pile.

Results from Run 1 for pressure measured with the load panel and for pile heights are presented in Figure III-11. The initial part of the pile build-up could not be obtained because of an unexpected inflow of residues from mill operations during the first shift on November 16. Wall deflection data were not measured.

The pancake cell indicated a wall pressure of 4.1 kPa for the duration of the test and did not respond to changes in pile height. Later removal and inspection of residues in front of the pancake cell indicated that although some wood residues were up to 30 cm long, no pieces were bridging across the cell to cause measurement errors. The discrepancy between the pressure measurements from the two sensors and the insensitivity of the pancake cell to changes in loading conditions is attributed to an ineffectiveness of the cell for measurement of pressures imposed by coarse residues.

The average and range of the size distribution of hog fuel for all four test runs are presented in Figure III-12 along with bulk density (as received) and moisture content for each run.

During build-up, the pile was three-dimensional in character in that the pile sloped towards the wall as well as parallel to the wall. The pile in front of the sensors became two-dimensional in shape once the next section of the bin had been filled.

2. Run 2 - November 23 - 24

Following Run 1, the hog fuel was discharged from the bin according to normal procedures, leaving a dormant pile of triangular cross section against the wall in front of the pressure sensors. This material was left in place for Run 2.

Results for build-up on top of this small dormant pile are shown in Figure III-13. A similar dormant pile was present at the start of Run 3. Lateral pressure increased from an initial value caused by the dormant pile. Bin wall displacement at the panel increased with pile height to a value of near 30 mm, indicating substantial wall flexibility and an active pressure regime.

The pancake cell registered 1.0 kPa at the start of Run 2, a value much less than registered by the load panel. As during Run 1, the pancake cell was insensitive to pile height changes. The indicated value was not consistent with the 4.1 kPa pressure registered during Run 1. A check of the pancake cell system by the

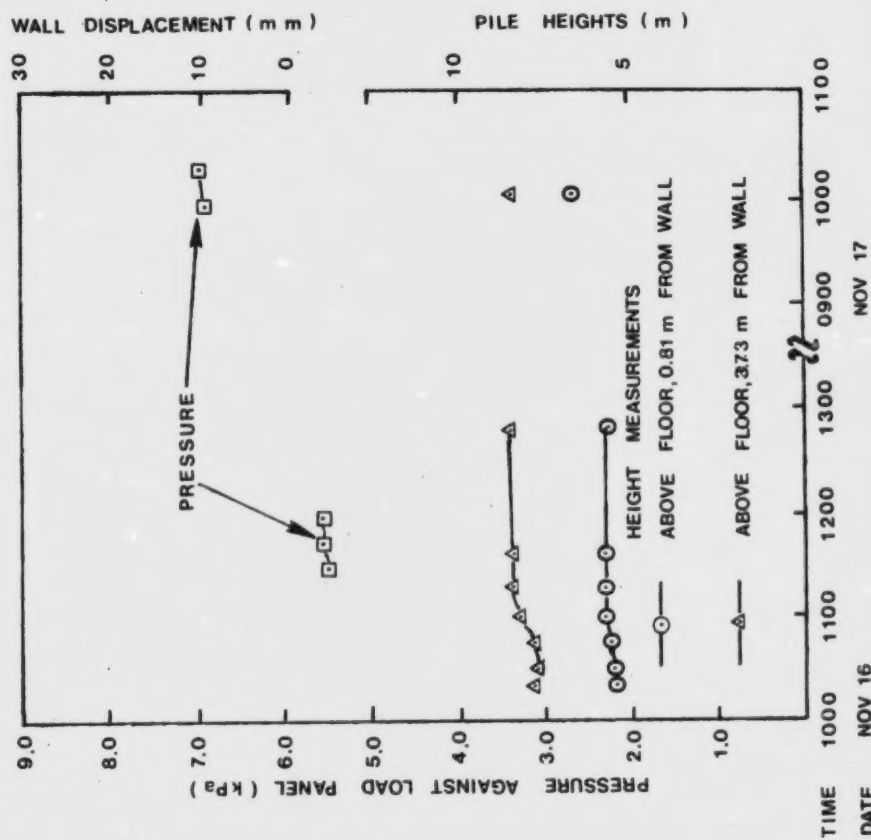


FIGURE III-11 LOAD PANEL DATA FOR NOV 16-17

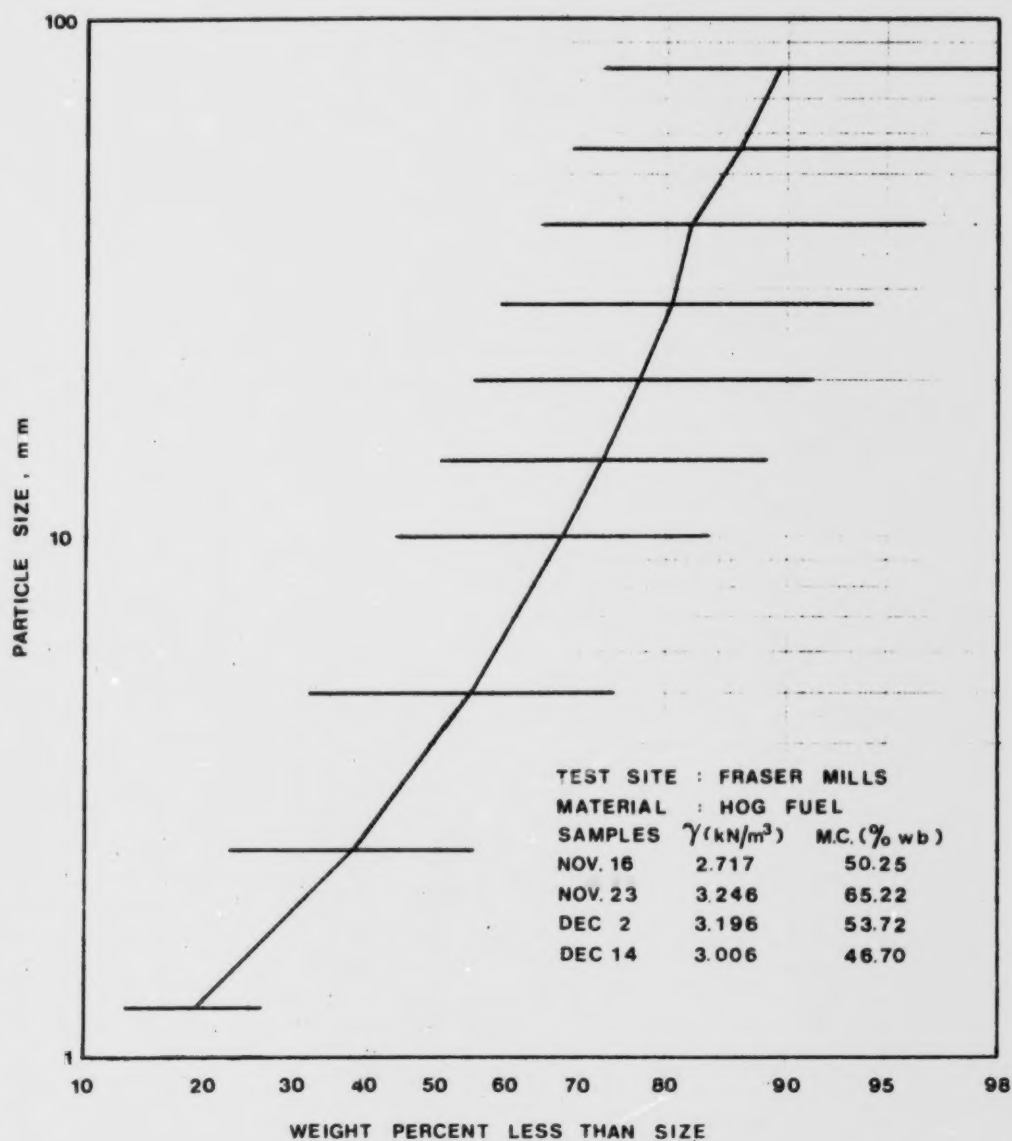


**FIGURE III-12 SIZE DISTRIBUTION OF HOG FUEL FOR
 HEIGHT TEST IN PHASE I**

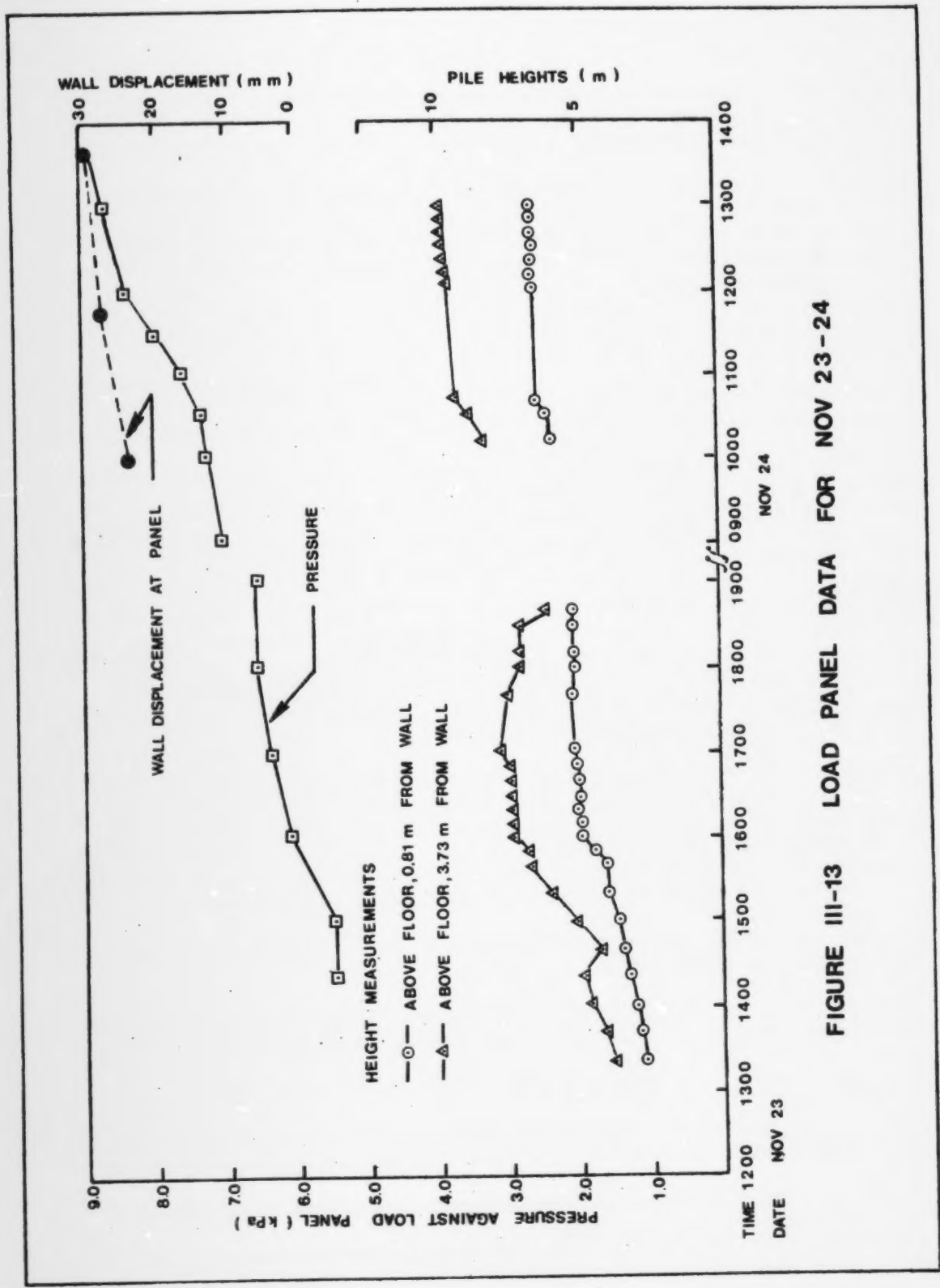


FIGURE III-13 LOAD PANEL DATA FOR NOV 23-24

manufacturer on November 24 showed the unit to be functioning properly. At this time, the indicated value of 2.0 kPa was still much less than the 6.1 kPa pressure indicated by the load panel.

The lateral pressure on the load panel during draw-down of the pile with the hydraulic rake is presented in Figure III-14. No pile heights could be measured during the draw-down of the pile, since the sounders would have interfered with operation of the hydraulic rake.

3. Run 3 - December 1 - 4

In preparation for Run 3, the material in front of the pressure sensors was cleared away on November 29. At this time, an in-field calibration of the pancake cell system was conducted.

An unexpected infeed of material occurred while instruments were unattended on November 30. The pile reached full height at about 2100 hours on November 30 and was added to during the duration of sampling on December 1. The pressure indicated by the pancake cell at 1420 hours was only 1.7 kPa.

The pile in front of the pressure sensors was reclaimed with the hydraulic rake before the next series of test measurements commencing at 0930 hours on December 2. Prior to this run, a small pile remained against the wall which had been dormant for about 37 hours. The shape of the dormant pile and the pile shape during build-up are presented in Figure III-15.

The lateral pressure at the load panel and pile height data are summarized in Figure III-16 for the December 2 build-up and for December 4, by which time the pile had achieved a two-dimensional shape and remaining sections of the bin had been filled. From December 1 to December 4, only a slight increase in pile height had occurred compared to a remarkable increase in pressure.

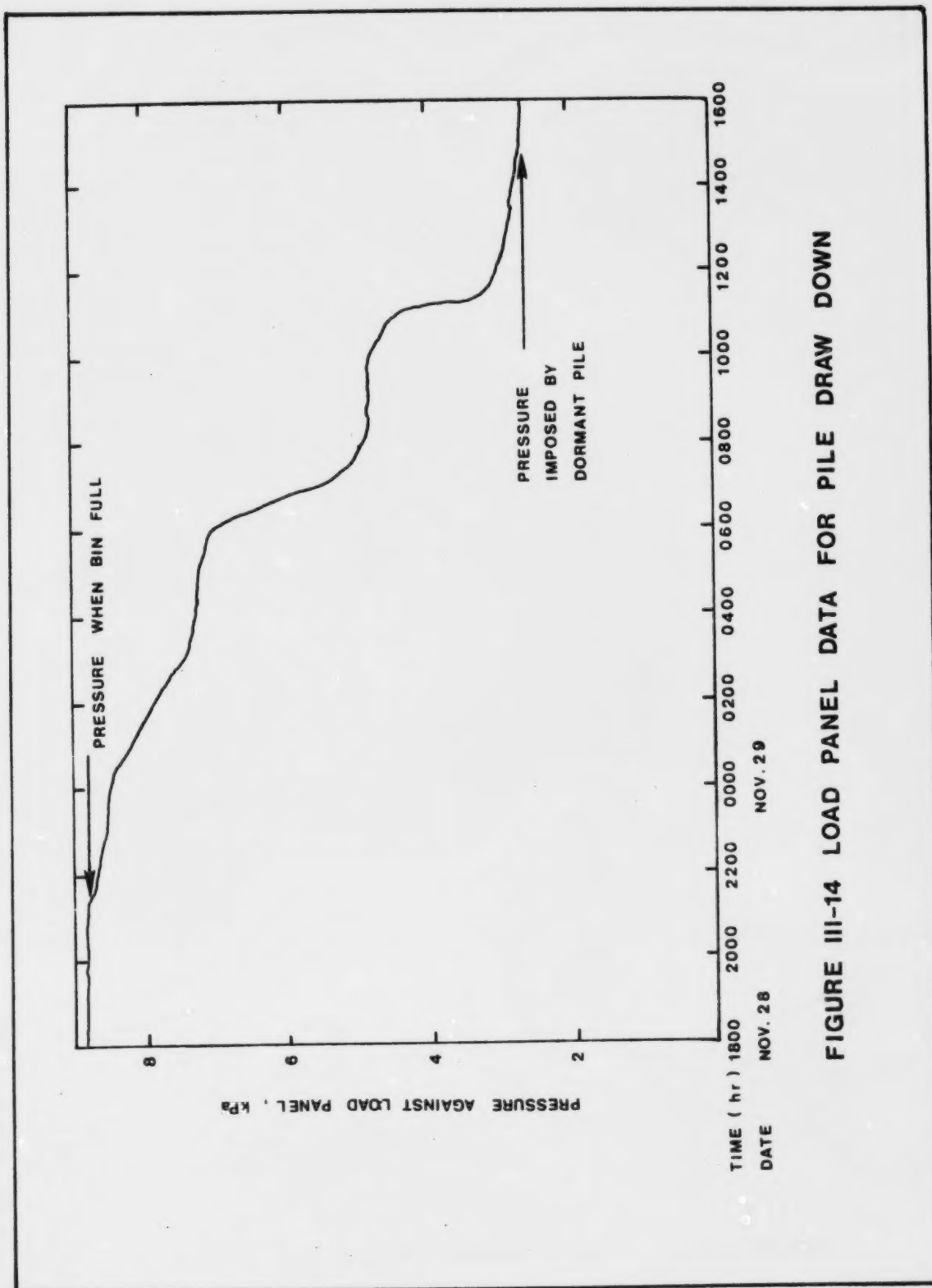
Bin wall deflection increased to 25 to 30 mm, as had been observed during Run 2.

The pancake cell still registered a much lower pressure than registered by the load panel and was insensitive to pile height.

4. Run 4 - December 14 - 18

The pile in front of the pressure sensors was cleared away to floor level on December 13 in preparation for Run 4.

The pile cross section during build-up from floor level is illustrated in Figure III-17 for December 14. Pressure and height data presented in Figure III-18 show the correlation of pressure with pile height.



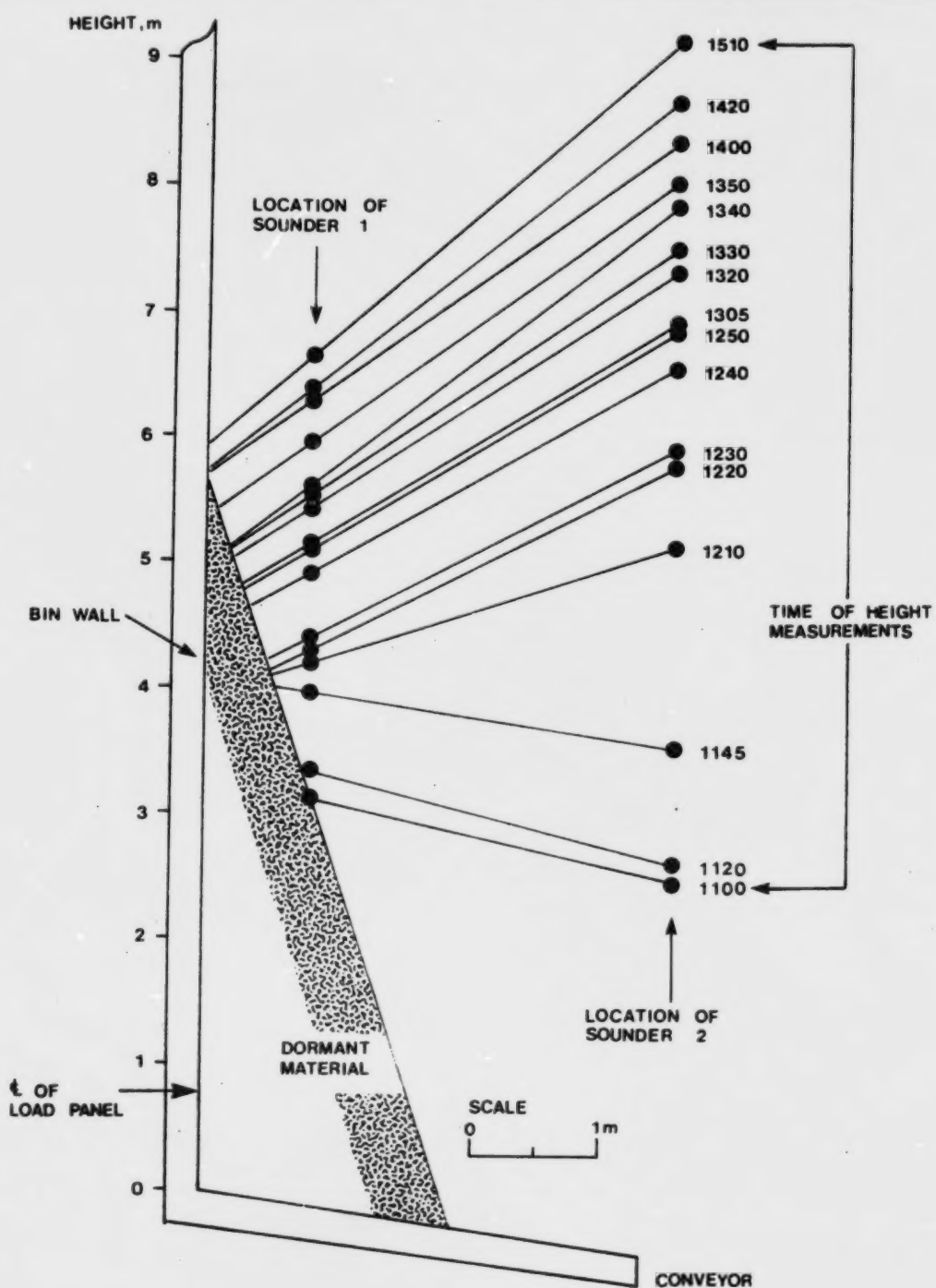


FIGURE III-15 PILE BUILD-UP ON DEC 2

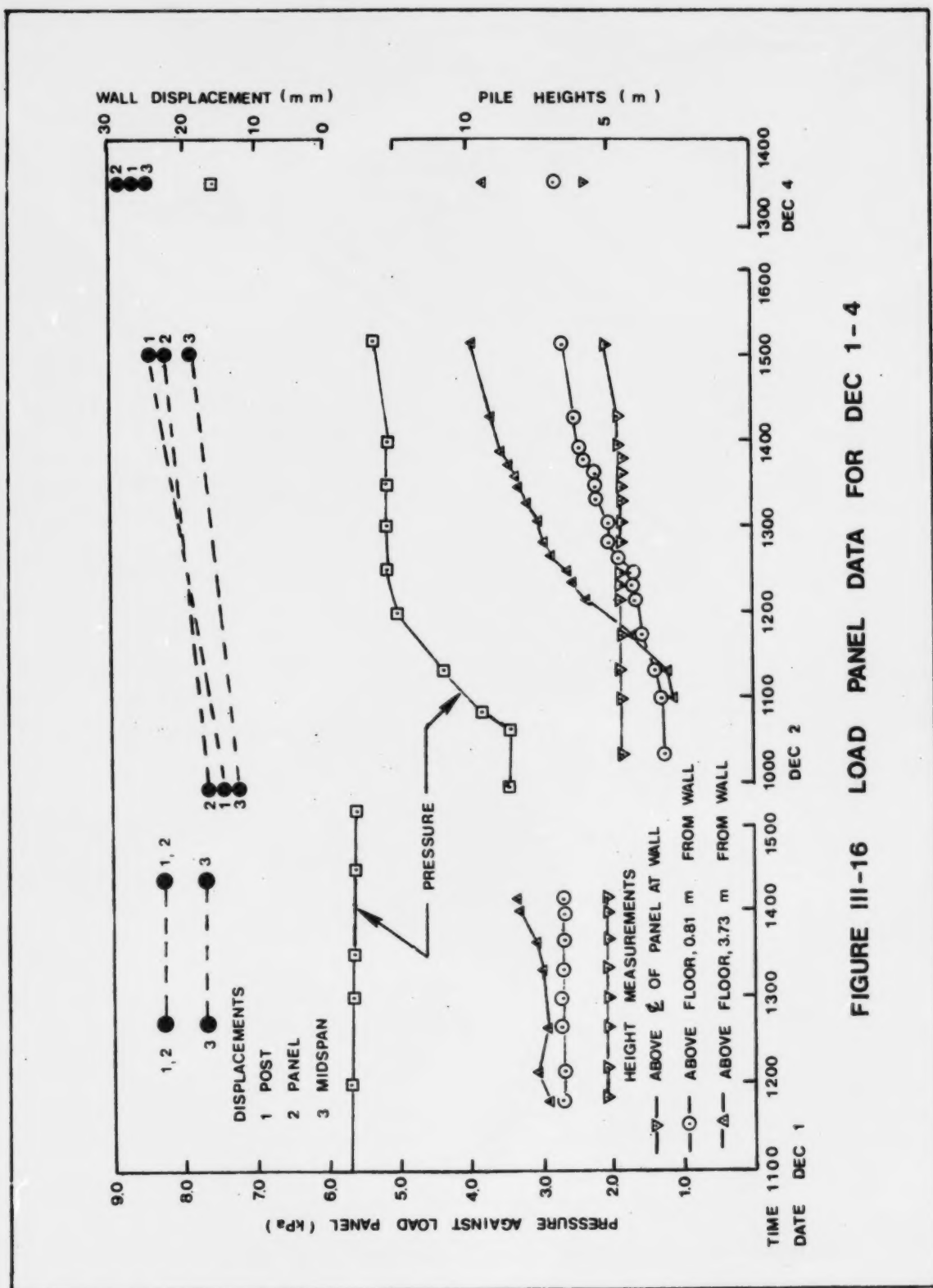
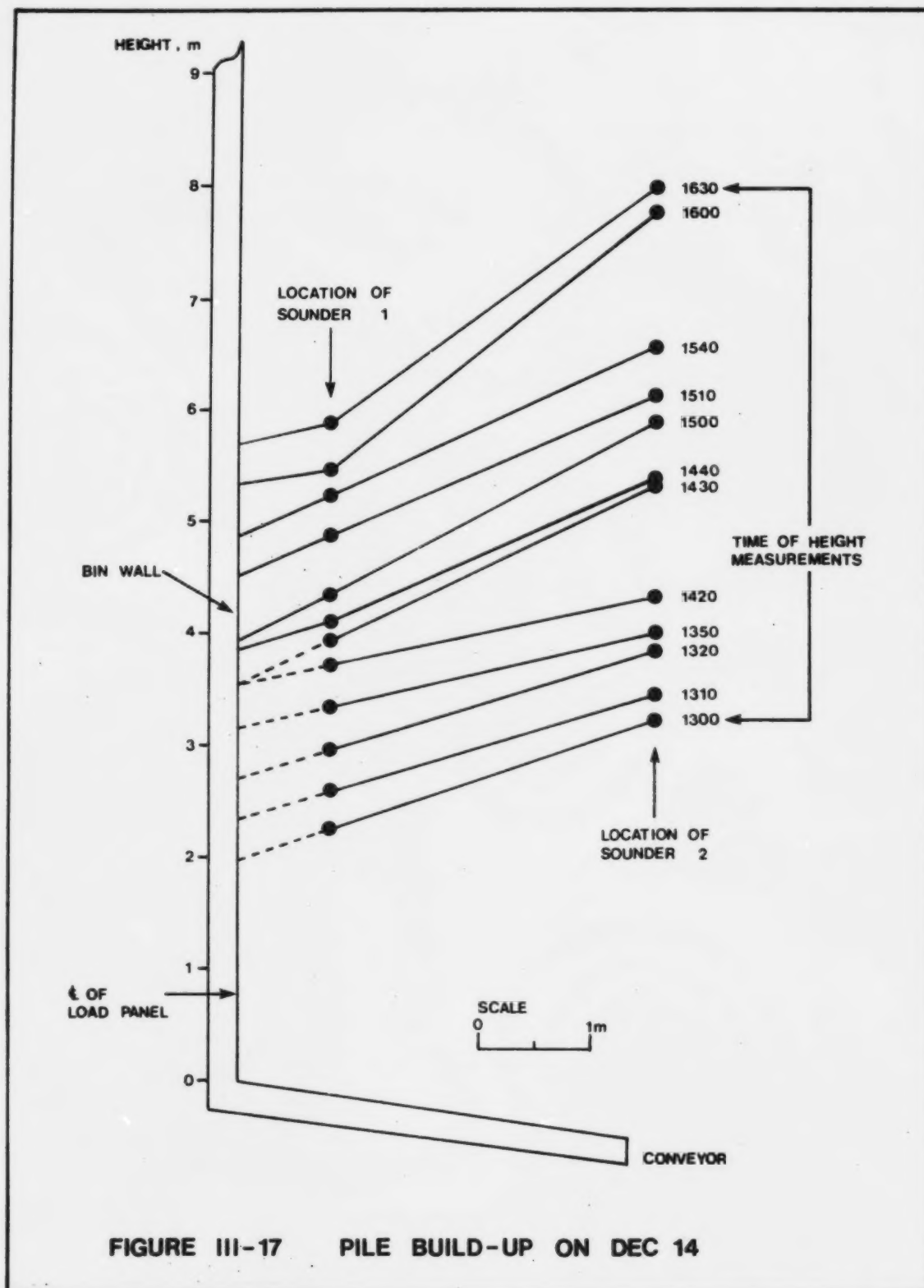


FIGURE III-16 LOAD PANEL DATA FOR DEC 1-4



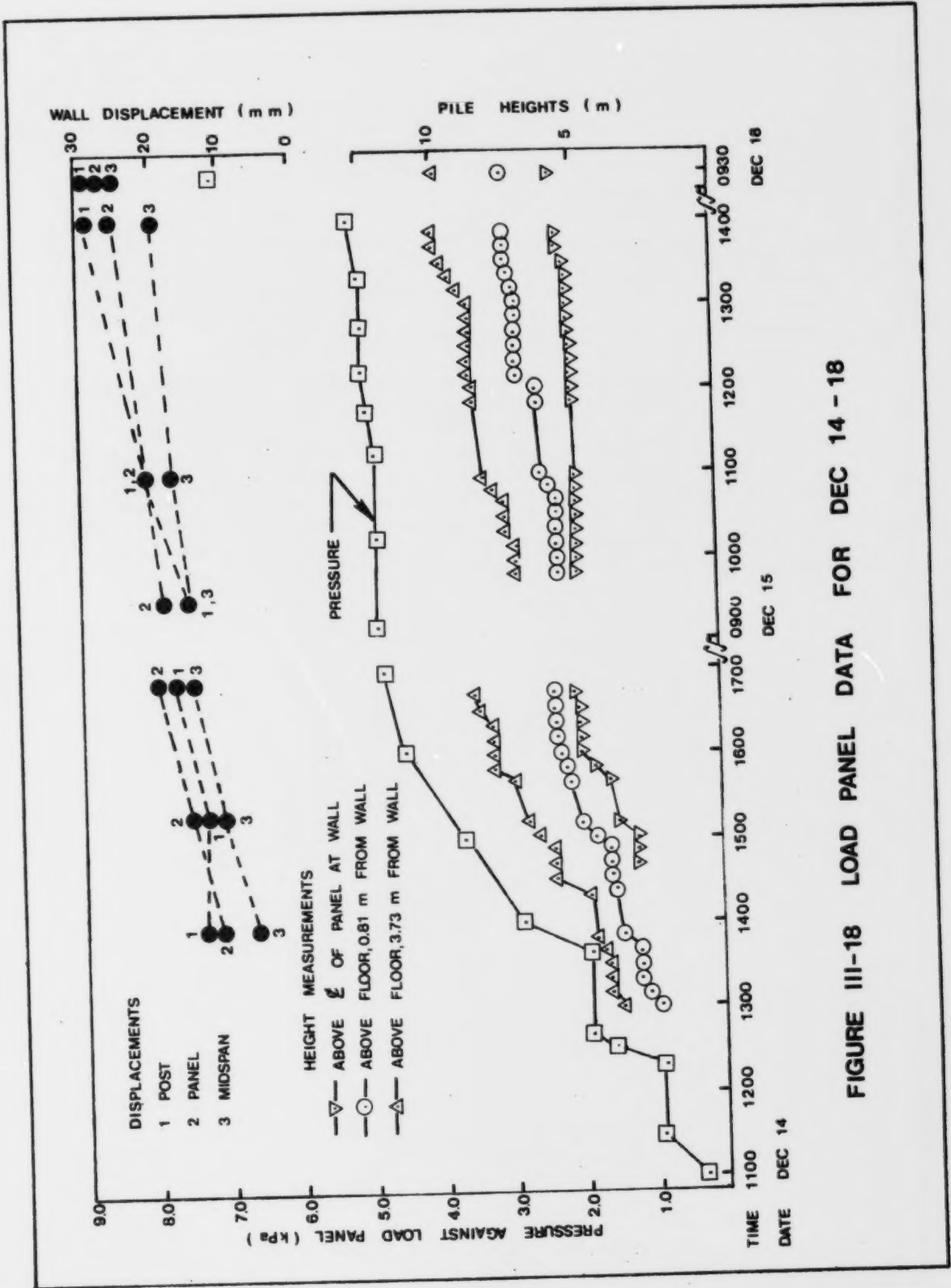
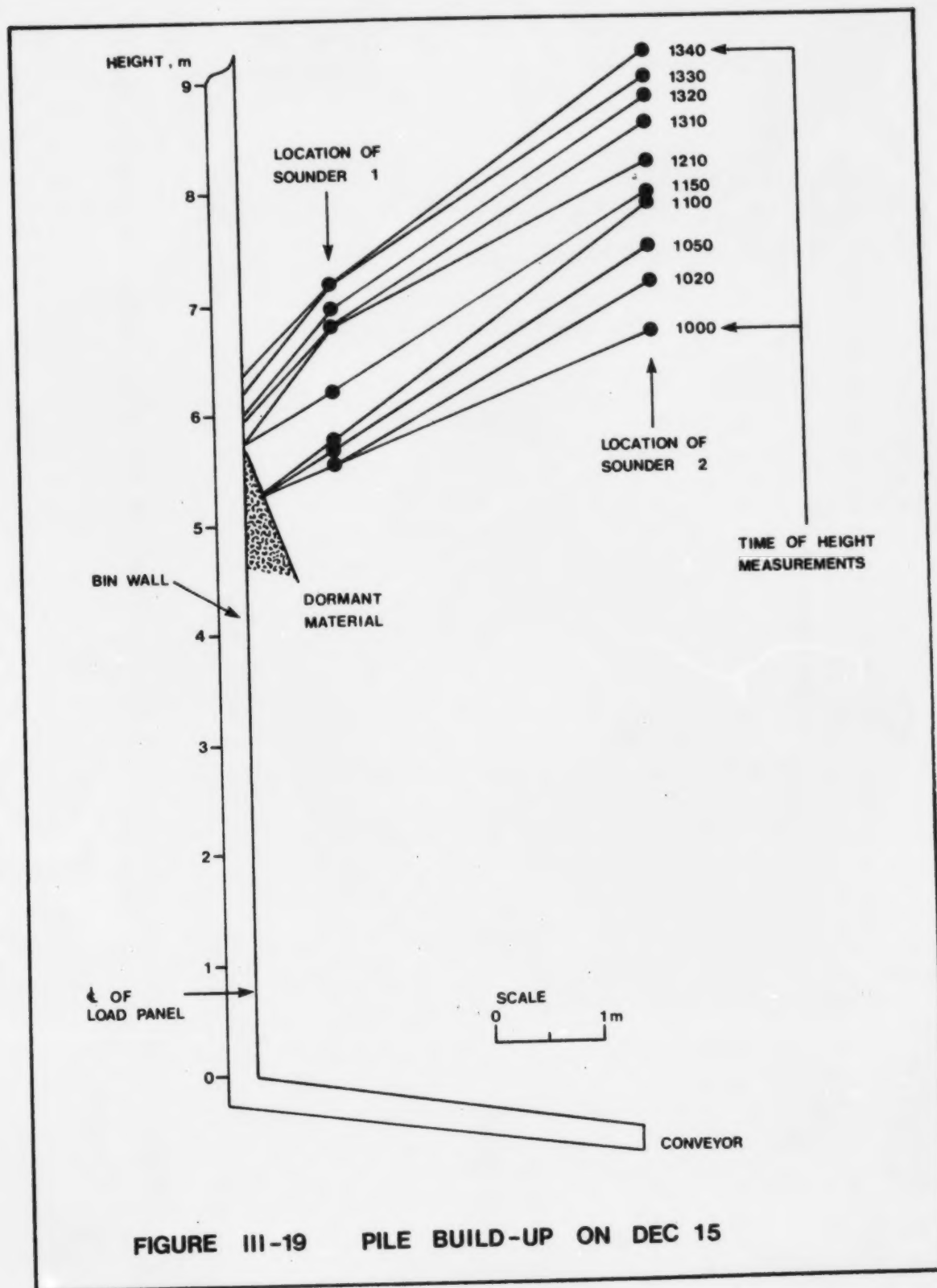


FIGURE III-18 LOAD PANEL DATA FOR DEC 14 - 18

A partial draw-down of the pile occurred during the first shift of December 15 prior to further pile build-up, as shown in Figure III-19. Pressure and height data for the continuation of pile build-up on December 15 is consistent with data for December 14 (Figure III-18).

The final data points for this run were obtained at the end of the week (December 18). As for Run 3, pressure increased substantially, even though only a minor increase in pile height occurred. This pressure increase may be due to compaction of residues and the change from a two- to three-dimensional pile shape.

Figure III-20 shows the difference between pressures measured by the two sensors on December 14 and 15. The decline of the pressure registered by the pancake cell is inconsistent with the changes in pile height. Systematic and repeated inspection of the monitoring instrumentation for the pancake cell by the manufacturer and B.H. Levelton and Associates Ltd. staff during the series of test runs did not identify any equipment malfunctions. The erratic and apparent erroneous data from the pancake cell is attributed to its unsuitability for this application with wood residues.



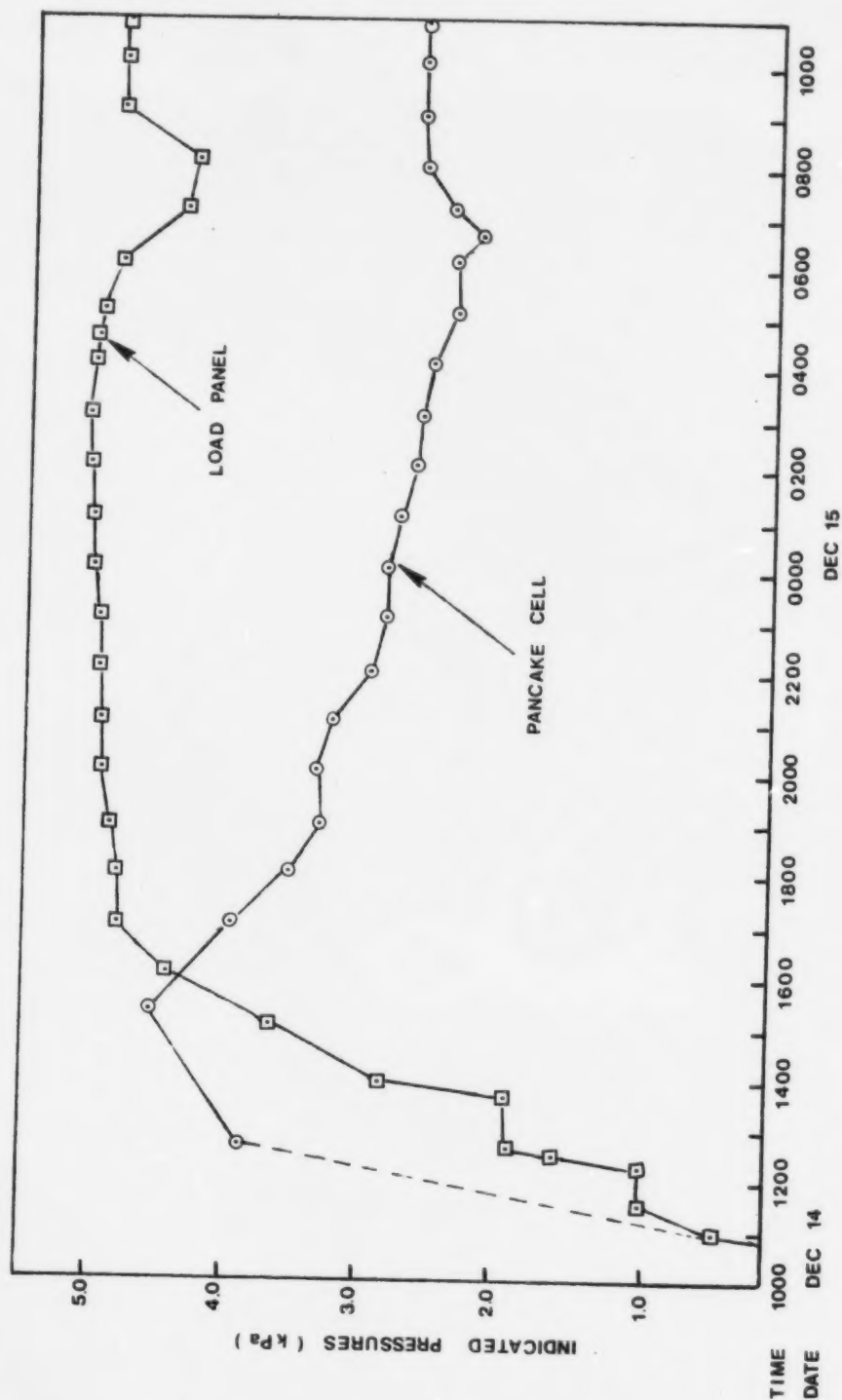


FIGURE III-20 COMPARISON OF PRESSURES INDICATED BY THE LOAD PANEL AND PANCAKE CELL

IV. PHASE II TESTS

A. Objectives

The objectives of Phase II were to:

- determine the variation of lateral pressure with the depth of the fuel pile;
- determine the variation of lateral pressures on a retaining wall as the pile ages;
- determine the effect on lateral pressure of vehicle traffic (bulldozers, etc.) on top of the fuel pile;
- analyze and interpret the test data to develop relationships to assist the design of retaining structures.

The test program in Phase II concentrated on the gathering of pressure data using the most suitable pressure-sensing system developed during Phase I.

The analysis and interpretation of the data from Phase I and II tests are dealt with in Chapter V.

B. Test Site Description

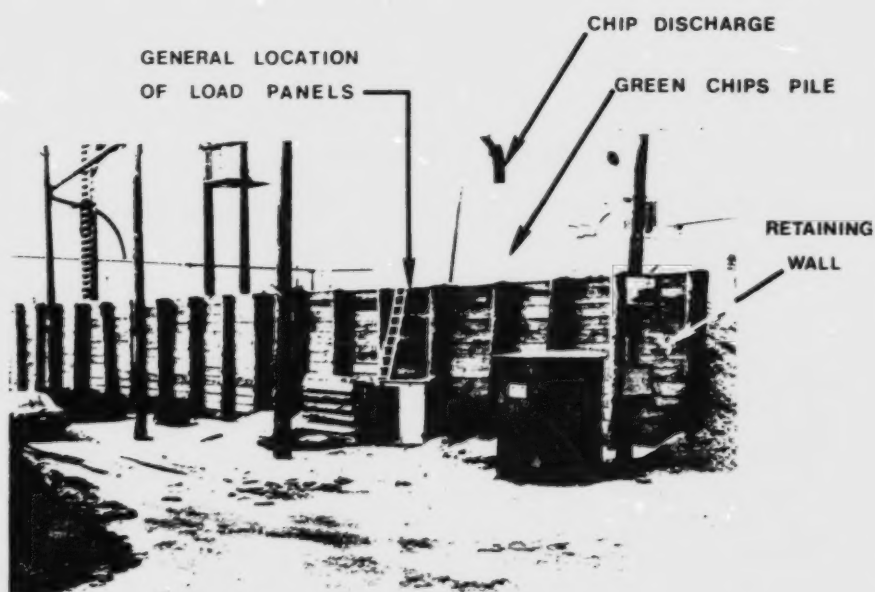
Most of the tests for Phase II were carried out at:

Canadian Forest Products Ltd.
Plywood and Hardboard Division
440 Canfor Avenue
New Westminster, B.C.

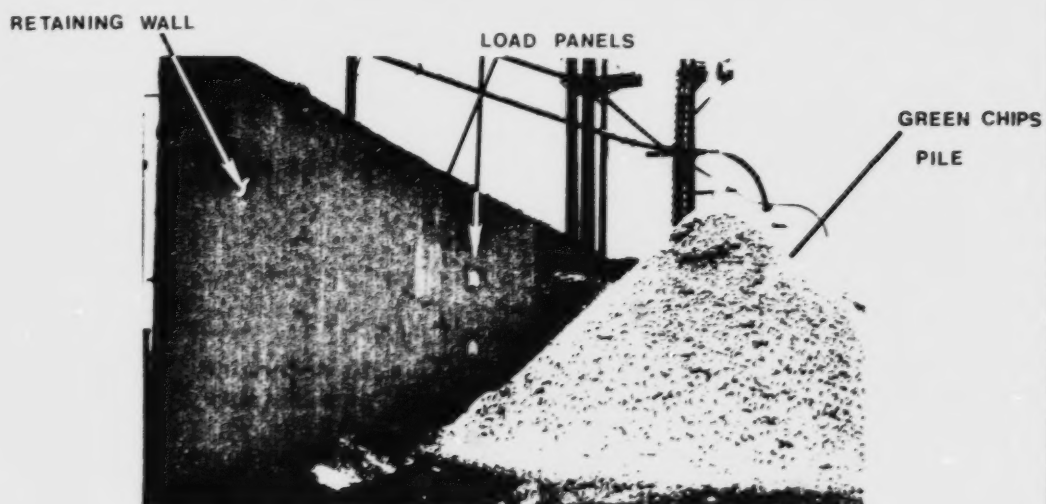
One further test run was done at Fraser Mills to determine the pressure distribution on the bin wall as a function of pile height.

The Canadian Forest Products (Canfor) site (Figure IV-1) was selected because a long retaining wall (0.3 km) was present with facilities for outdoor storage of hog fuel and green chips and operating conditions that enabled testing for the effects of pile height, vehicle traffic, and age on lateral pressure.

The retaining wall is 4.4 m high and constructed of 7.6 cm X30.5 cm lumber covered by 1.9 cm plywood on the side facing the fuel pile. It is supported at the back by 30.5 cm diameter timber columns at 1.5 m spacing.



A. BACK OF RETAINING WALL



B. FRONT OF RETAINING WALL

FIGURE IV-1 PHOTOGRAPHS OF THE RETAINING WALL
FOR GREEN CHIPS AT THE CANFOR MILL

The green chip pile was used for the tests measuring the effect of pile height. These chips are transported from the sawmill by an overhead pneumatic conveyor and discharged vertically downward onto the ground near the retaining wall. Material accumulates and forms a conical pile with its peak reaching the discharge outlet of the pneumatic conveyor and its base touching the bottom of the retaining wall. To avoid plugging up the discharge outlet, the pile is routinely broken-down by a front-end loader and pushed onto the retaining wall. In order to eliminate the effect of the loader during build-up of the pile, the pneumatic pipe was shortened so that the pile was built-up against the wall to its full height.

Green chips are directed to the storage pile starting Monday morning and continue to build-up for three to four hours, until the pile reaches the full height of the wall (4.5 m). The pile is normally reclaimed over the weekend using a front-end loader.

Hog fuel at the Canfor test site is obtained from other mills for use in the boilers and is transported to the site by self-unloading trailers. Small piles of hog fuel unloaded from the trucks are gathered by a front-end loader to form one distributed pile with an irregular, though roughly flat, top. As the pile size reaches some intermediate height, more fuel is added by driving and unloading the trailers on top of the piles. A small, tracked bulldozer occasionally levels the top surface of the pile.

The age and vehicle tests were carried out at the same location on the hog fuel retaining wall.

C. Modified Load Panel Pressure Sensor

The load panel system developed in Phase I was modified and used to measure all the lateral pressure data in Phase II. Modification of the design used in Phase I was done to minimize the damage to the retaining wall and simplify installation.

The modified load panel system (Figure IV-2) operates on the same principle as the load panel used in Phase I. The load panel was mounted on a wooden frame leaving about 12 mm clearance between the panel and the wall. A plastic strip was used to cover the gap between the panel and the frame to avoid jamming by residues. Two 16 mm holes were drilled through the wall for the load rod and the counterweight cable. The load cell was anchored on the steel bracket mounted with lag bolts to the back of the retaining wall (Figure IV-3).

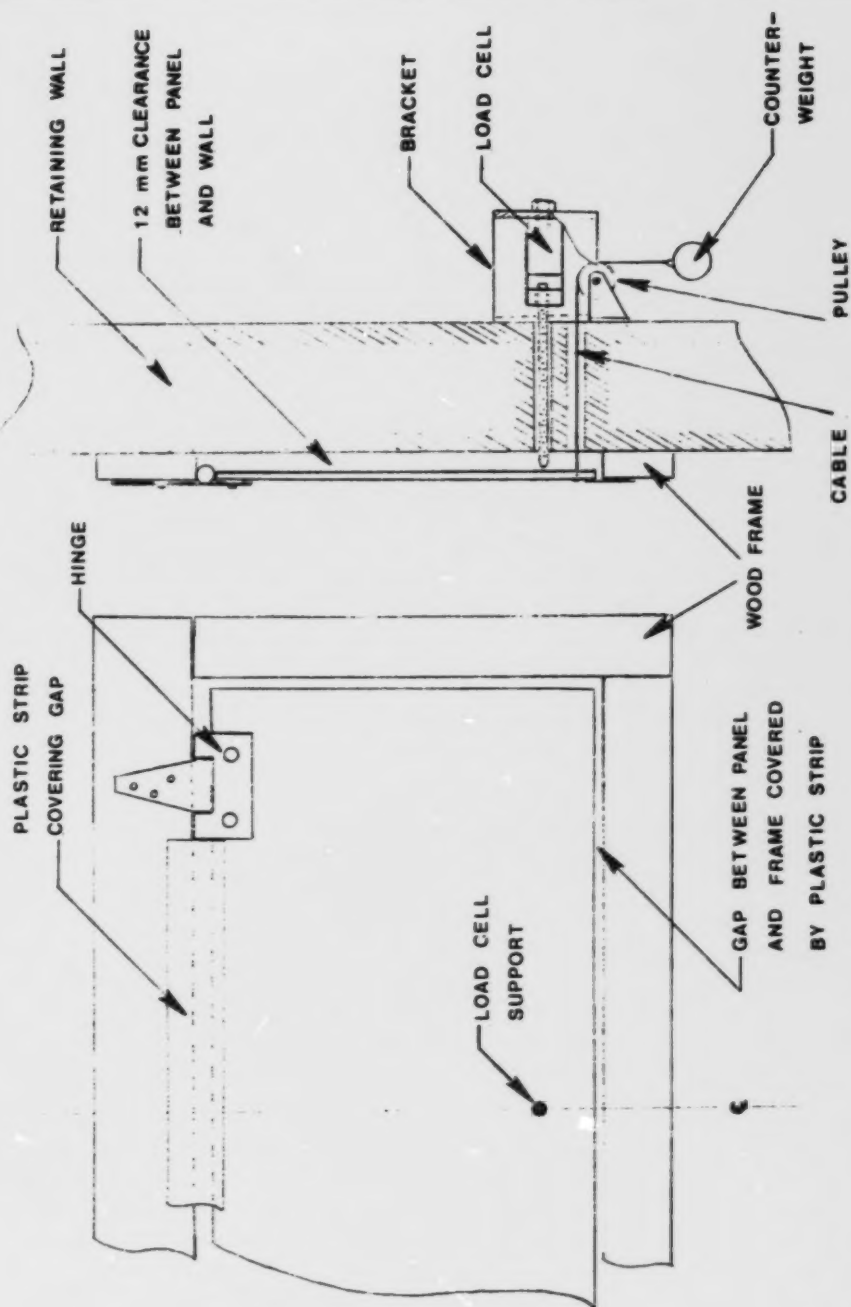


FIGURE IV-2 MODIFICATION OF LOAD PANEL FOR PHASE II

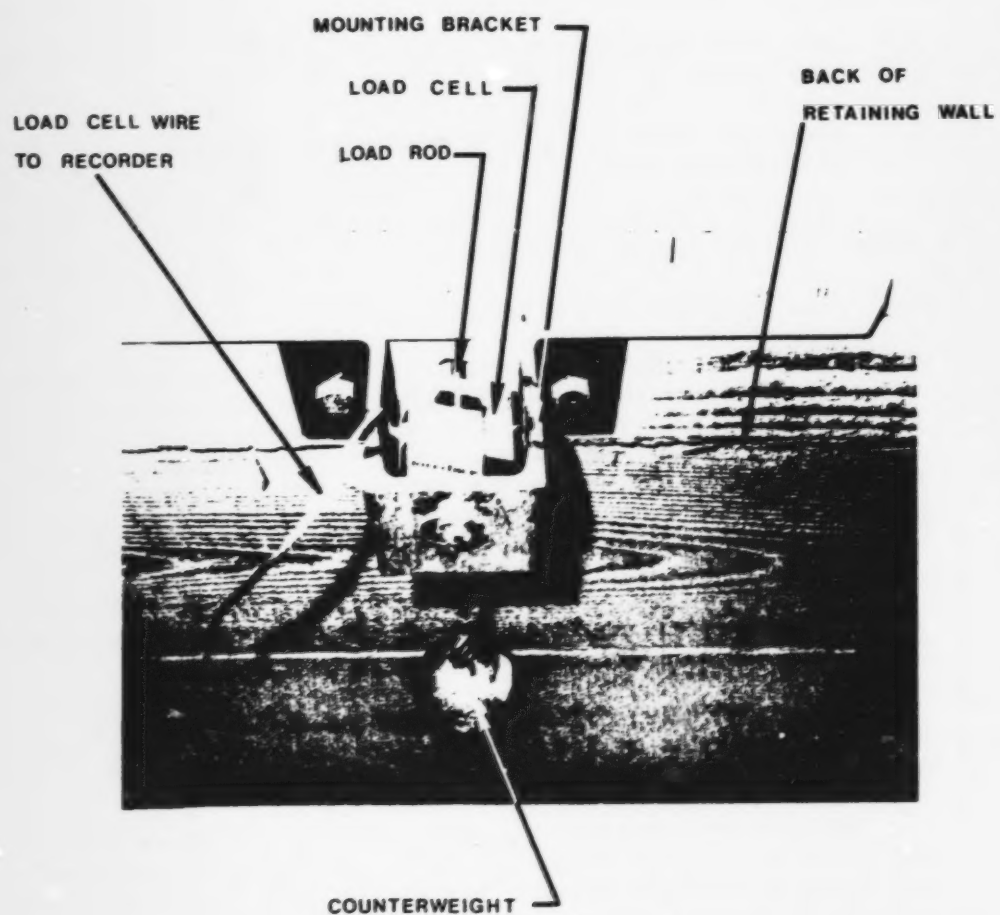


FIGURE IV-3 DETAIL OF LOAD CELL MOUNT
USED FOR PHASE II

The modified load panel had the following specification, depending on the load cell capacity:

load cell capacity (N)	- 2,224	1112
load panel capacity (kPa)	- 20	10
output (mV/kPa)	- 1.5	3.0
accuracy (kPa)	- ± 0.07	± 0.03
displacement (mm)	- < 0.2	< 0.2

D. Effect of Pile Height on Pressure

1. Data Measurements and Procedures

Three test runs were carried out at Canfor using the green chip pile to determine the variation of lateral pressure with the depth of the pile. The tests were done on February 22, March 1, and March 8. Three vertically-aligned load panels at different heights were used to measure the lateral pressure (Figure IV-4). The output signals from the three load panels were recorded continuously on a strip chart recorder during pile build-up.

Pile heights were measured manually at 10 minute intervals using two mechanical sounders, one at the wall, and the other at 0.9 m from the wall (Figure IV-4).

Samples of green chips were collected during each test. Physical properties of the material were determined using the same methods described in Phase I.

An additional test of the effect of pile height was done at the Fraser Mills site on May 4. Three vertically-aligned load panels mounted 0.78 m, 1.64 m, and 2.53 m above floor level were used to measure the lateral pressure. A load panel was also mounted on the floor of the bin such that the centerpoint was 37 cm in front of the wall. This panel could not be placed farther from the wall as desired due to the existence of a protective steel floor covering. The dormant pile of hog fuel at the bin wall was cleared away prior to the test. Other data such as pile heights and material characteristics were measured and analyzed as stated in Phase I.

Checks of the instrumentation were conducted routinely to ensure all equipment was functioning properly. These checks confirmed reference and signal voltages and ensured that the load panels were active; load panels were checked by monitoring output voltage differentials resulting from a change of the panel counter-weight.

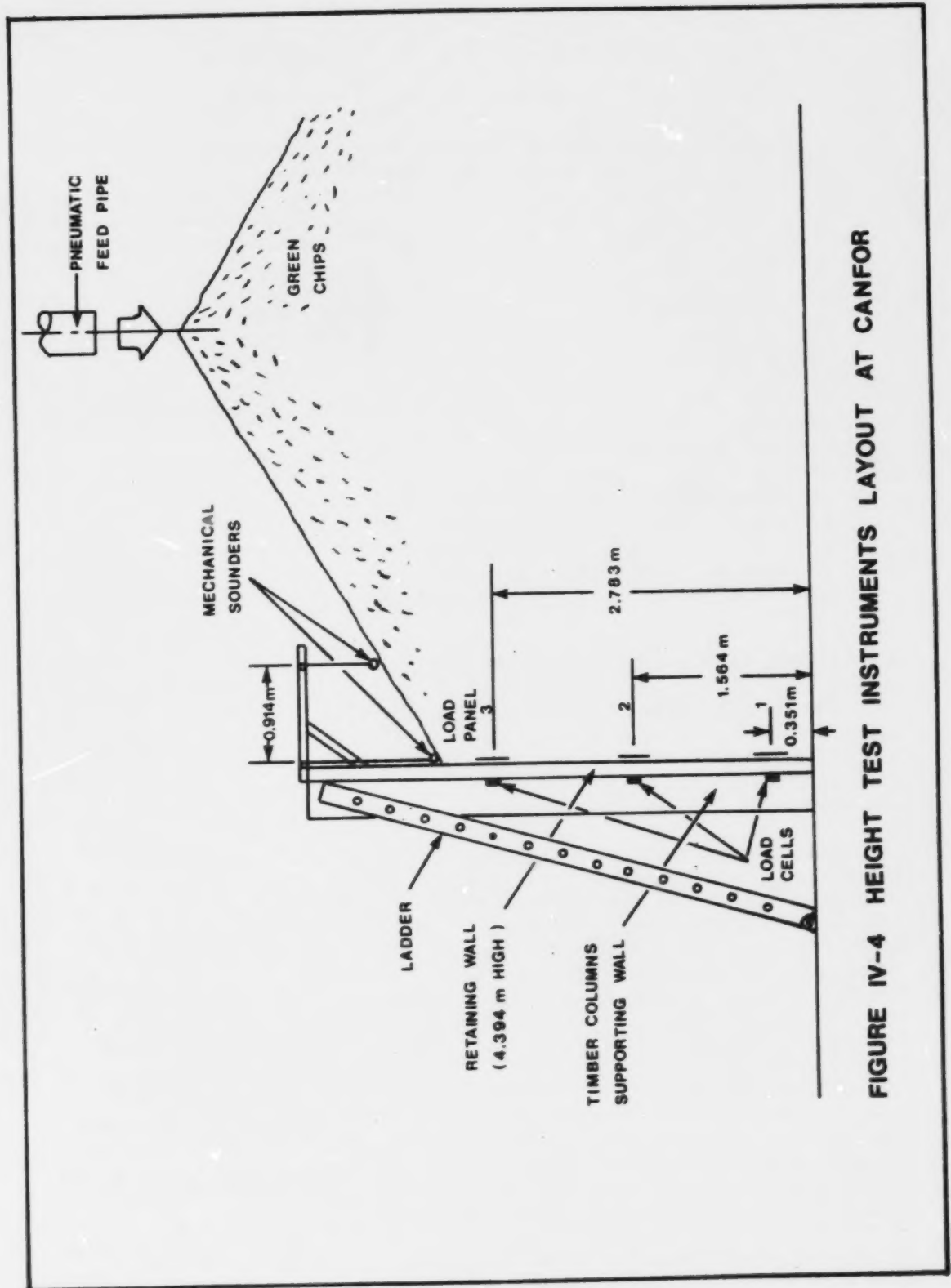


FIGURE IV-4 HEIGHT TEST INSTRUMENTS LAYOUT AT CANFOR

2. Test Results

Three test runs were conducted at the green chip pile with the pile building freely against the retaining wall. During the test, no material was reclaimed from the pile so that it took on a conical shape having a height of 6.8 m and base diameter of 9.5 m when built to maximum size. The center of the pile was about 3.6 m from the wall.

Results of the test runs at Canfor are presented in Figures IV-5, IV-6, and IV-7. A plot of the size distribution of the green chips is given in Figure IV-8.

The results from the additional test run at Fraser Mills are presented in Figures IV-9 and IV-10. Characteristics of the material are given in Figure IV-11. The procedures for this test were generally as described for Phase I. The unusual response of the floor panel is believed to be due in part to its proximity to the wall. The effects of repeated loading are shown by the data gathered during the weeks following the initial pile build-up. This cyclic loading is normal practice and, as the data show, increases wall pressures significantly.

E. Effect of Pile Age on Pressure

The tests to determine the variation of lateral pressure with pile age was carried out with the hog fuel at the Canfor mill. A load panel was installed on the retaining wall 0.703 m above ground to measure the lateral pressure exerted by the hog fuel pile. The voltage output of the load panel was monitored using a multimeter and recorded manually.

The load panel output was recorded daily at the beginning of the age test. After the lateral pressure leveled off within 0.2 kPa, the load panel output was monitored regularly within 7-day intervals. Samples of hog fuel were collected and analyzed to determine size distribution, bulk density, and moisture content (Figure IV-12). The sample obtained on February 2 consisted of a mixture of two separate samples of material gathered near the retaining wall during pile build-up. The remaining samples were gathered from the surface of the pile and vary as a result of weather.

In preparation for the test run, material was cleared from the retaining wall. After installation of the load panel, trucks unloaded hog fuel near the wall to be moved into final position with a front-end loader. Some compaction of material may have resulted from handling and piling with the loader, but this method of pile build-up is normal practice. The lateral pressure at the wall was monitored during pile build-up and was found to be highly transient; reaching, at one point, a value of 14 kPa. The final pile height at the wall, near the load panel was 2.77 m as measured from the panel centerpoint.

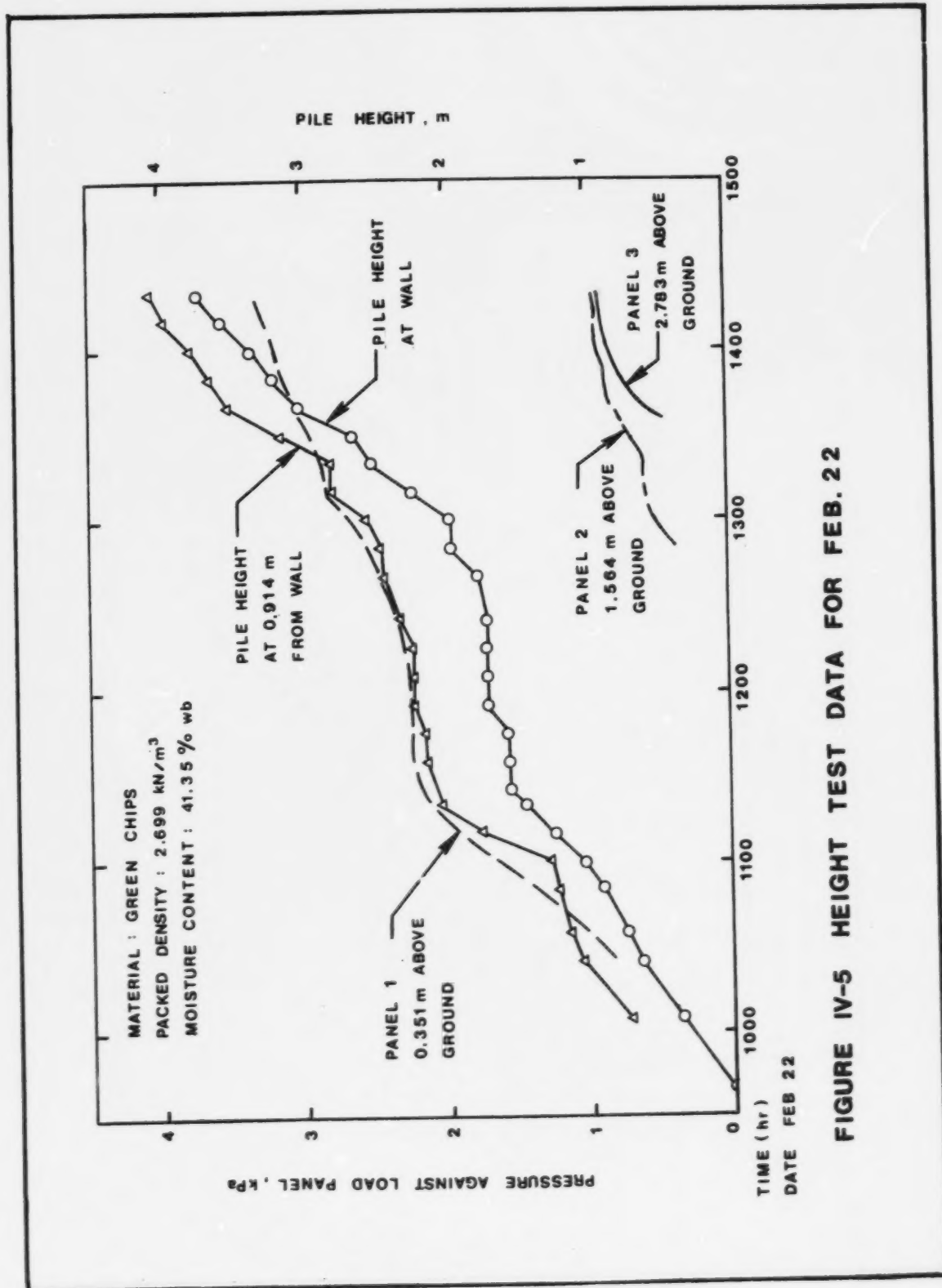


FIGURE IV-5 HEIGHT TEST DATA FOR FEB. 22

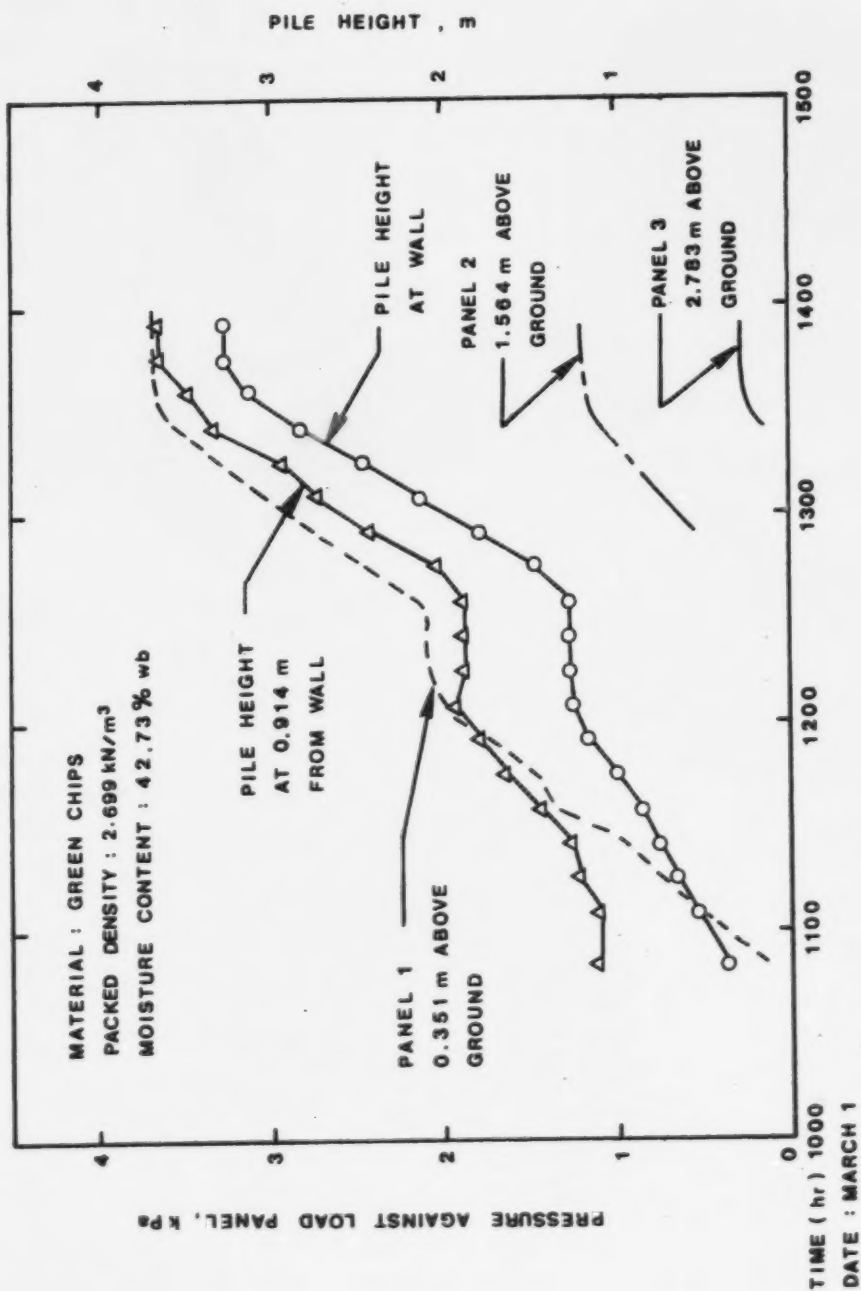


FIGURE IV-6 HEIGHT TEST DATA FOR MARCH 1

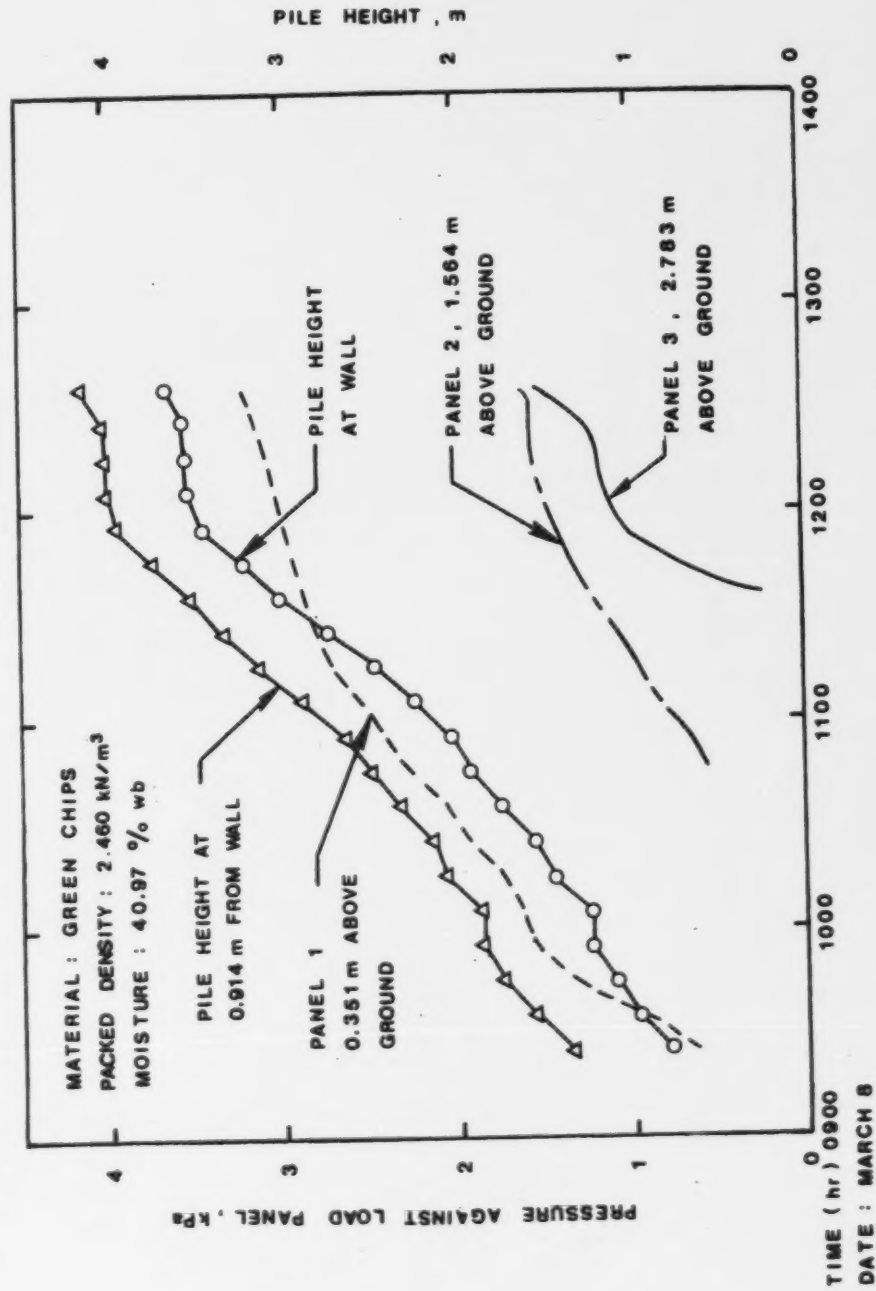


FIGURE IV-7 HEIGHT TEST DATA FOR MARCH 8

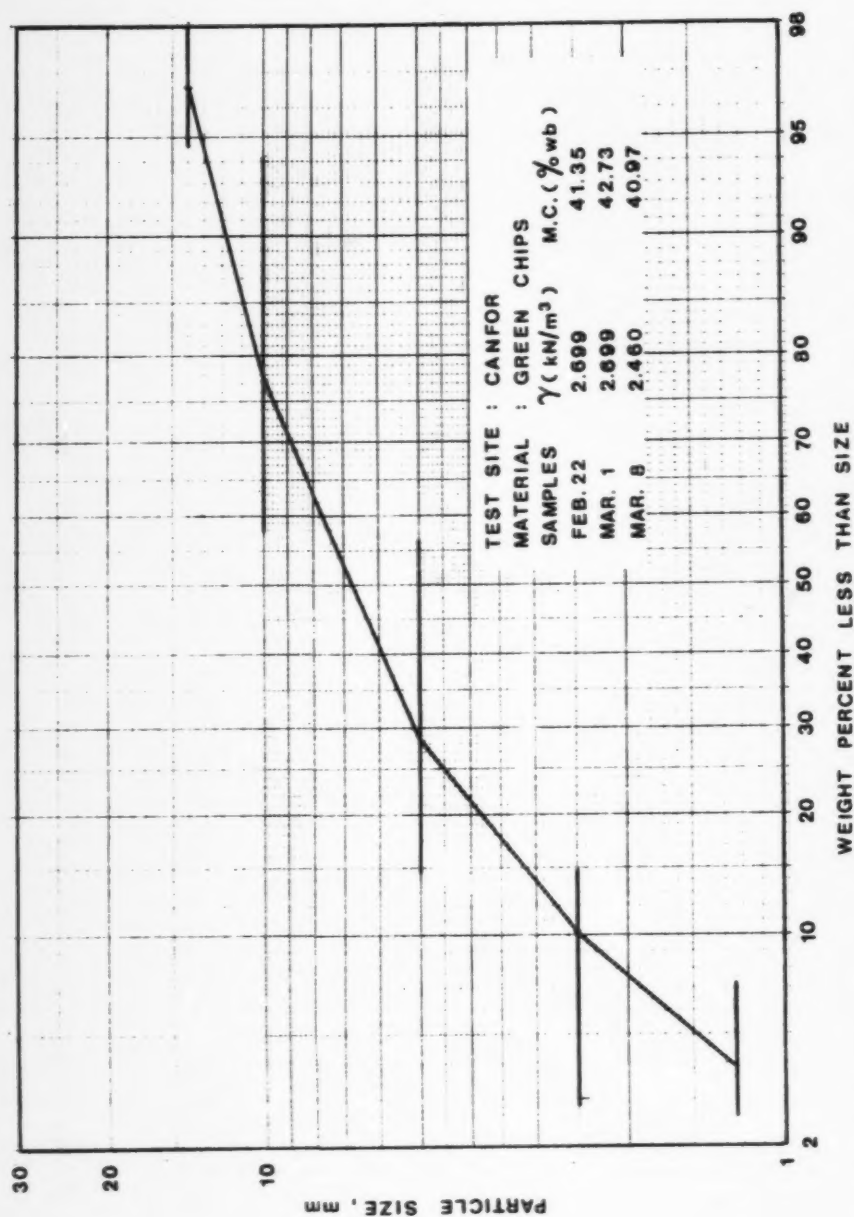
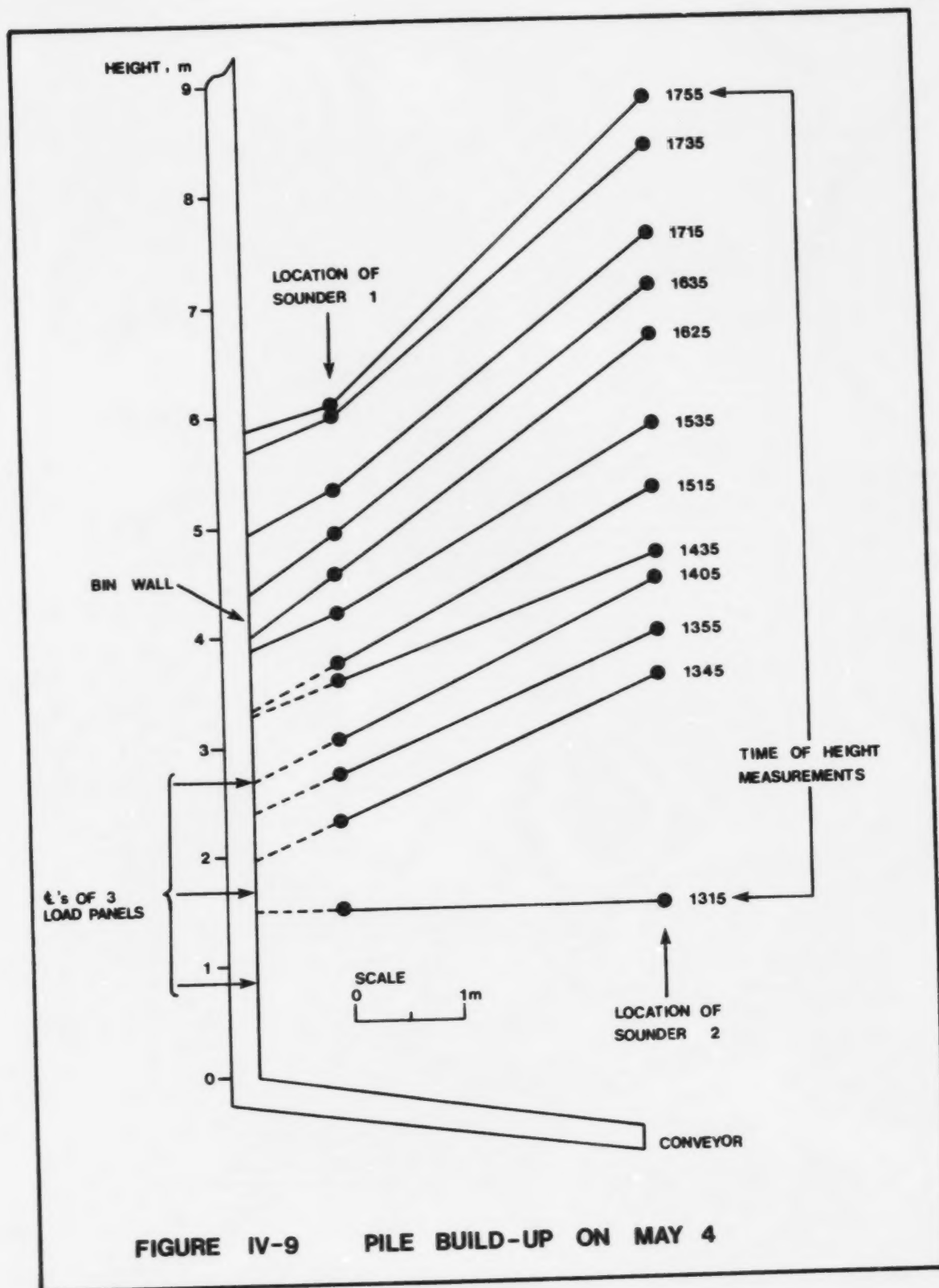
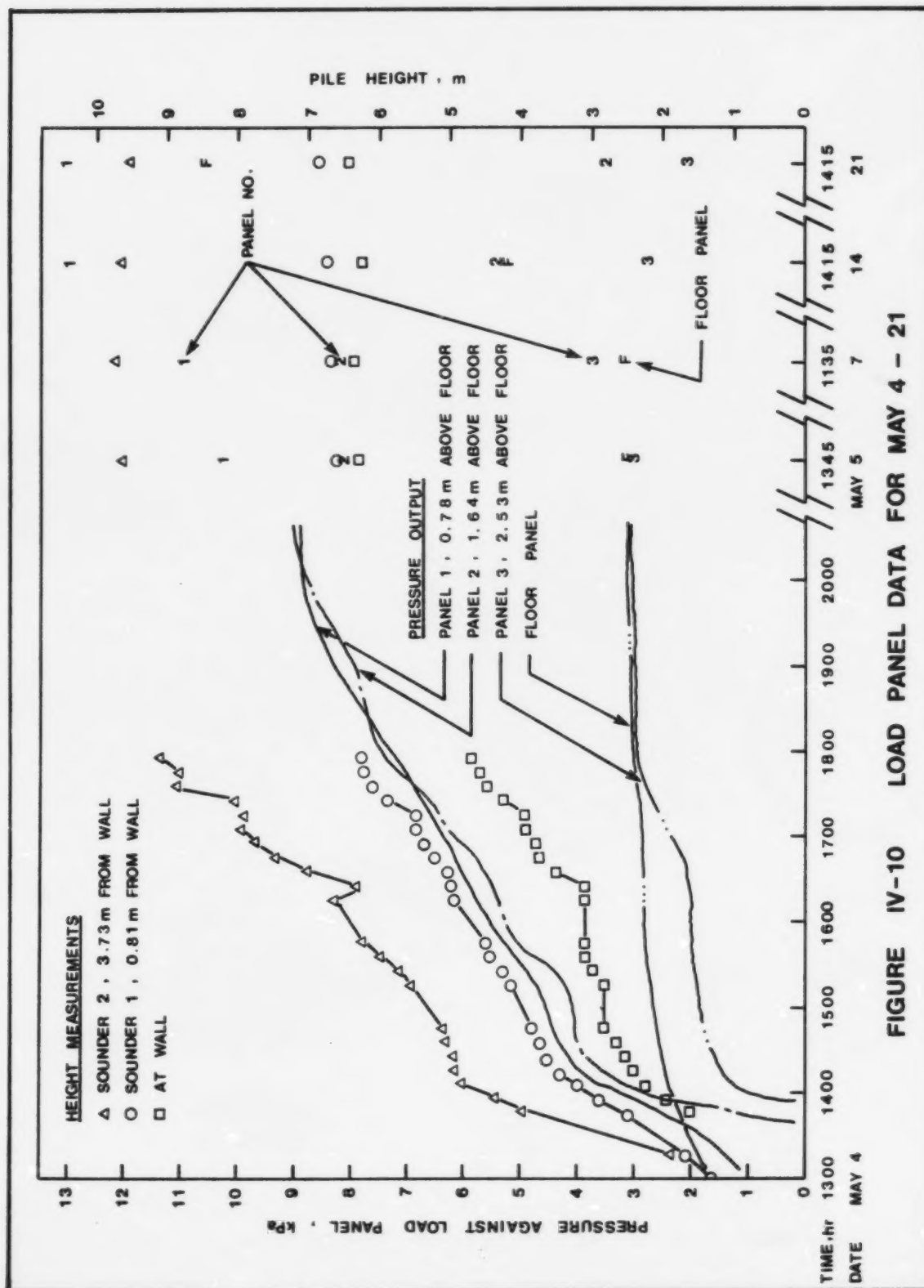


FIGURE IV-8 SIZE DISTRIBUTION OF GREEN CHIPS FOR HEIGHT TEST





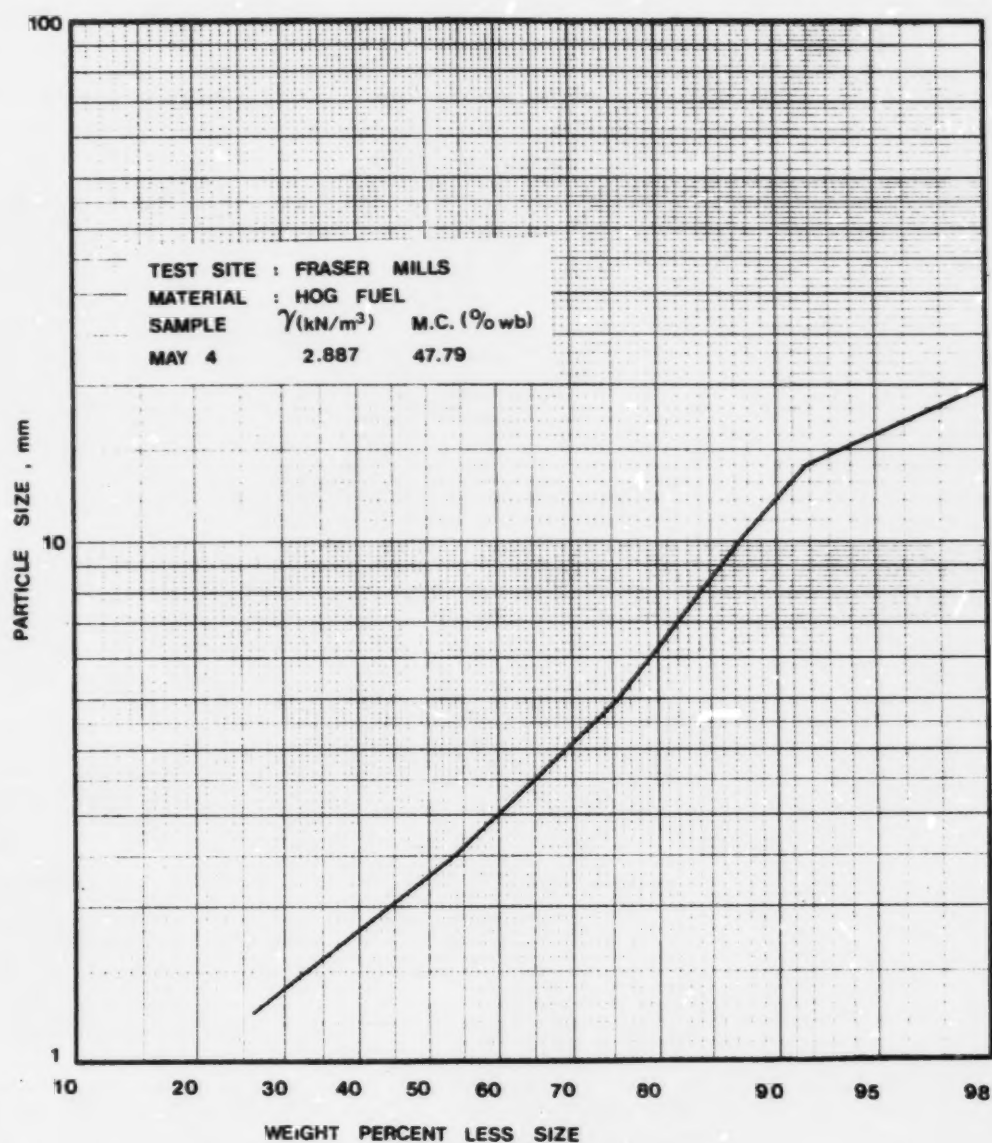


FIGURE IV-11 SIZE DISTRIBUTION OF HOG FUEL FOR
HEIGHT TEST IN PHASE II

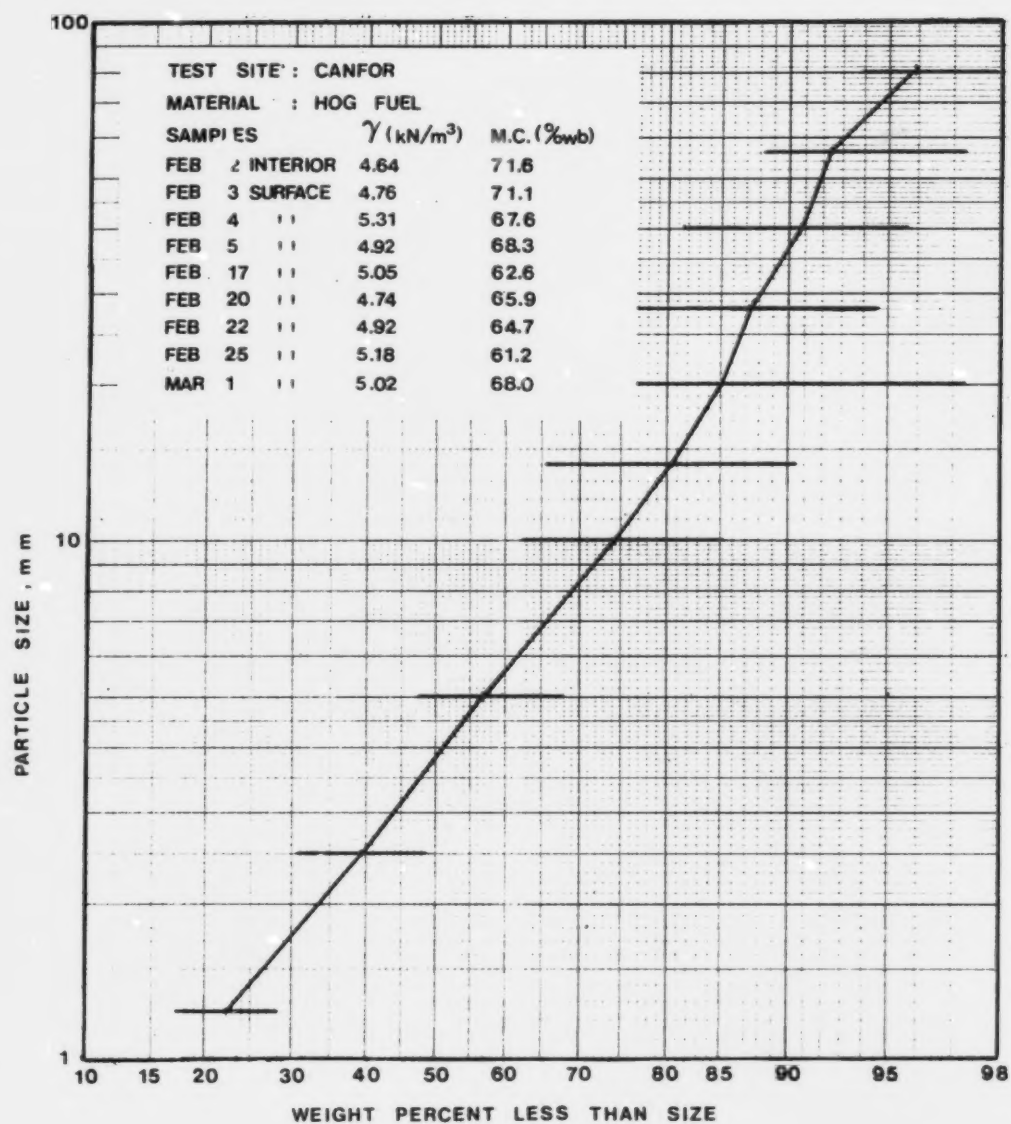


FIGURE IV-12 SIZE DISTRIBUTION OF HOG FUEL
FOR AGE TEST

Ten days after the initial build-up of the hog fuel pile, the valleys in the pile near the load panel were filled up manually. The surface contours of the hog fuel pile were then mapped (Figure IV-13).

Pressure dropped by about 0.8 kPa within three days after the initial build-up of the hog fuel pile (Figure IV-14). This might be due to the relaxation of the pressure imposed by the compaction of material by the front-end loader. The pressure then leveled off and remained quite uniform until material was added to fill the valleys present in the pile surface. This action resulted in a pressure rise of 0.45 kPa. Subsequent pressures fluctuated by only 0.3 kPa.

F. Effect of Vehicle Traffic on Pressure

A series of tests were conducted to determine the effect on lateral pressure of vehicle traffic on top of a fuel pile. Three load panels at 0.703 m, 1.784 m, and 2.869 m above ground were installed for this purpose at the site previously used for the age test.

After the load panels were installed, hog fuel was piled against the wall on March 30 and 31 in a manner similar to that for the age test. A bulldozer, which was later used in the test, was used to level the pile surface to give a final compacted pile height of 3.55 m above ground. Samples of hog fuel were collected and analyzed for size, bulk density, and moisture content (Figure IV-15).

The bulldozer (Figure IV-16) used in the vehicle test was manufactured by John Deere Tractor Co.:

model	: JD450
weight	: 7.6 tonnes
vehicle dimensions:	4.0 m long (including blade) X 1.7 m wide
track dimensions	: 2.7 m X 0.35 m
track spacing	: 1.35 m

Pressures were recorded continuously on a strip chart while the bulldozer was driven on top of the fuel pile running first parallel, then perpendicular to the wall at the location of the three load panels. Markers were put in lines parallel and perpendicular to the wall at 1.5 m intervals in an area within a 6 m radius of the load panels. The references for measurement of the bulldozer location were the vertical centerlines of the load panels and the bulldozer. The time when the bulldozer passed each marker was recorded so that the bulldozer location could later be related to the load panel reading on the strip chart recorder.

Six runs moving parallel to the wall, and seven runs moving perpendicular to the wall were made on April 1.

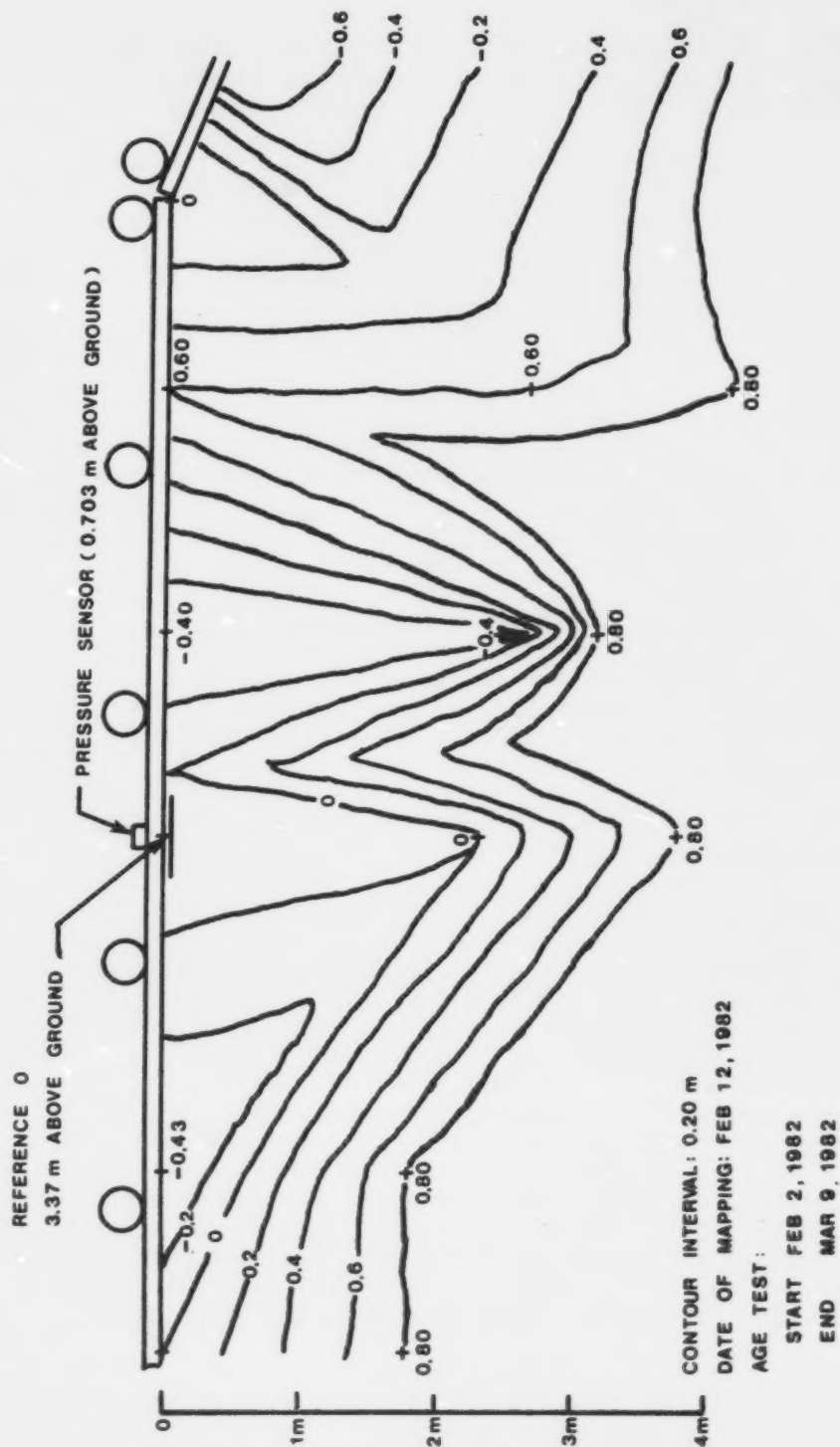


FIGURE IV-13 SURFACE CONTOURS OF HOG FUEL PILE USED FOR AGE TEST

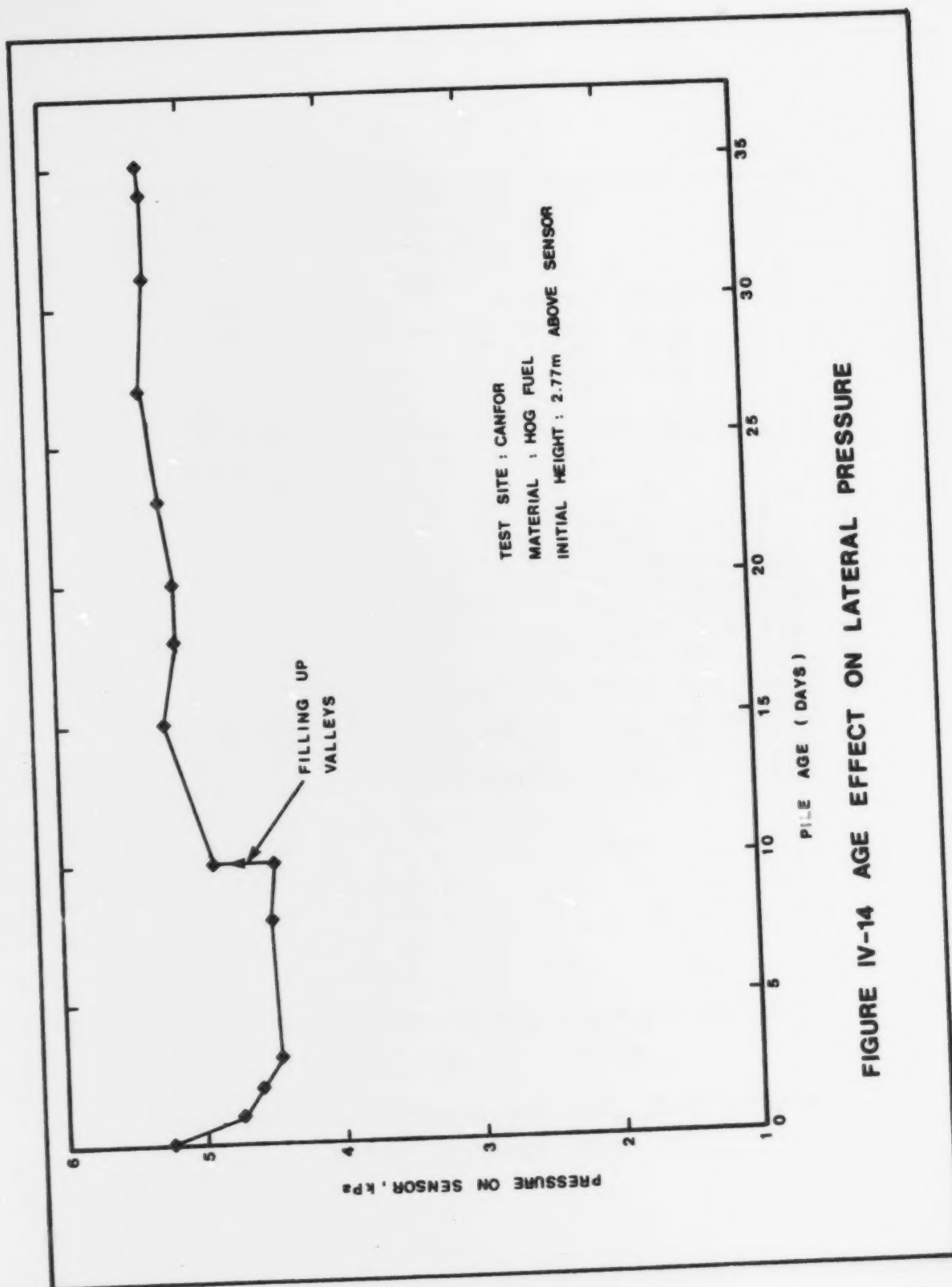


FIGURE IV-14 AGE EFFECT ON LATERAL PRESSURE

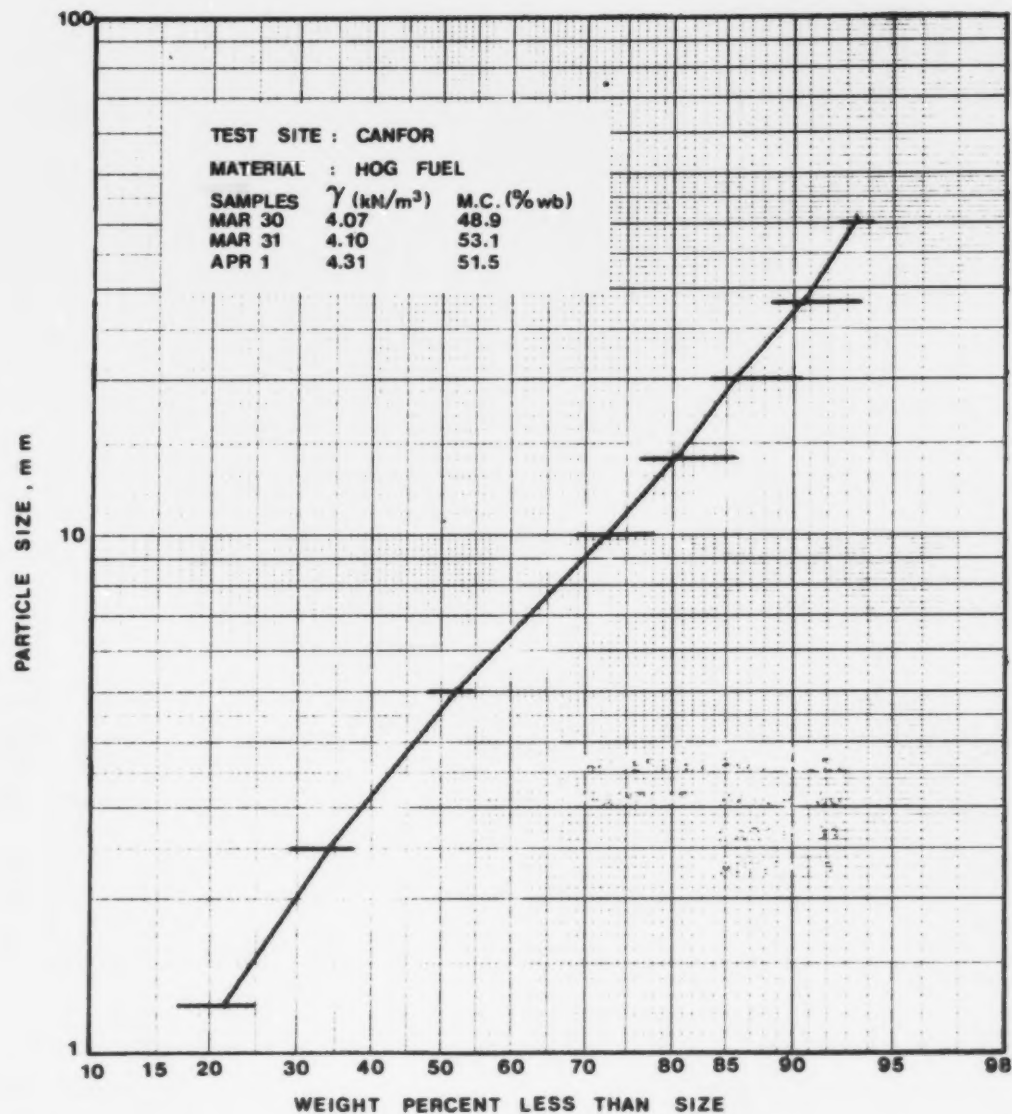


FIGURE IV-15 SIZE DISTRIBUTION OF HOG FUEL
FOR VEHICLE TESTS

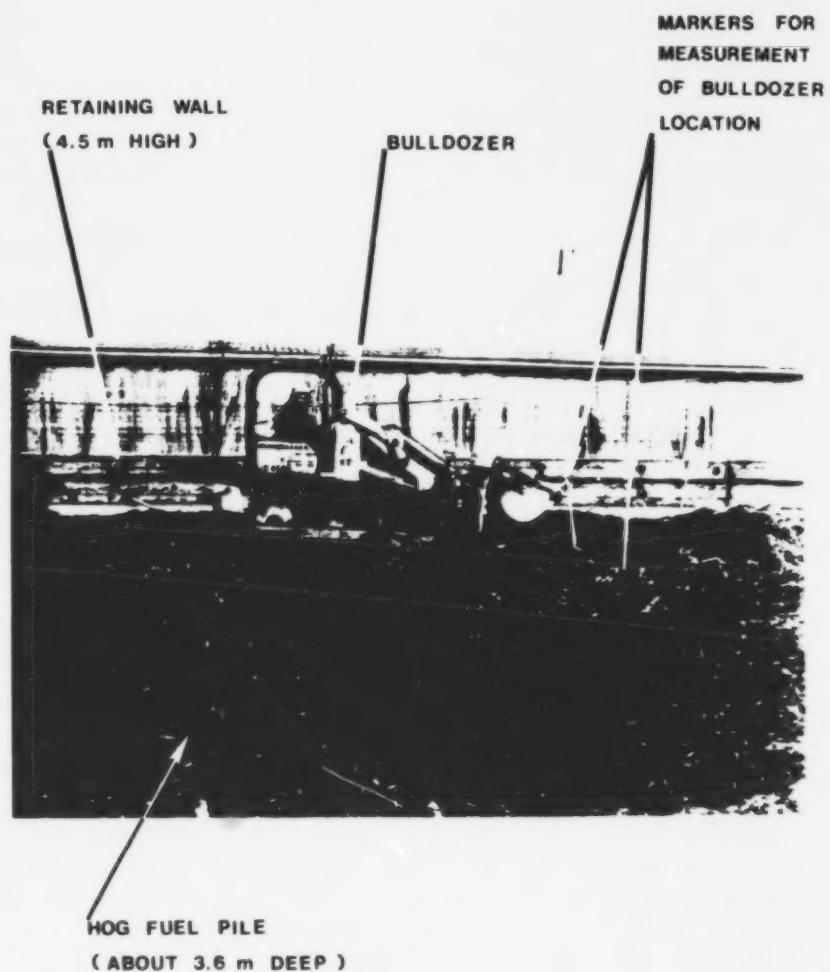


FIGURE IV-16 PHOTOGRAPH OF BULLDOZER AT
SITE OF VEHICLE TESTS

The following results of the vehicle tests are presented in chronological order.

1. Motion Parallel to Wall

After leveling of the pile with the bulldozer, an inverted pressure distribution existed on the wall. Prior to the bulldozer traffic, the pressure on the wall increased monotonically with depth. Compaction of the pile by the bulldozer caused the pressure to go through a submaximum at a depth near the first panel below surface (Panel 3). Panel 3 pressure was found to be greater than Panel 2 pressure, even though the latter panel was at a greater depth. The maximum pressure recorded was still at the bottom panel (Panel 1).

Runs 1 to 4 were conducted with the bulldozer travelling parallel to, and with the center of the vehicle 1.4 m away from, the wall. It started at about the 6.0 m location (Figure IV-17) to the left of the load panel, was driven forward at constant speed to the -3.0 m location to the right of the load panel, followed by a return in reverse at constant speed to the starting point.

A clear maximum occurred when the vehicle was directly in front of the pressure sensors. No change of the pressure at the bottom panel was observed. Note that the base pressure at Panel 3 (depth = 0.681 m) was greater than that of Panel 2 (depth of 1.766 m). No change in the pressure occurred at Panel 1.

2. Motion Perpendicular to Wall - Blade Down

Runs 5 to 7 were conducted with the bulldozer moving perpendicular to the wall in front of the load panels. Data was obtained while the vehicle moved toward the wall in forward gear and returned to the starting point in reverse gear. The blade was lowered but did not touch the pile surface. The center of the bulldozer moved from 4.6 m to 2.7 m from the wall.

Figure IV-18 shows the unusual, though consistent, results of these series of runs. Pressure at Panels 2 and 3 indicated a clear decrease in pressure. This behaviour is unexplained and, as far as is known, is not due to instrument malfunction. Runs 10 to 13 were a repeat of this test and indicated a pressure rise due to the vehicle; a response consistent with the results of runs with the bulldozer moving parallel to the wall, and supported by theory.

3. Motion Parallel to Wall - Discontinuous

Runs 8 and 9 involved moving the bulldozer parallel to the wall and stopping at each marker. Lateral pressures were found to be essentially identical to those for Runs 1 to 4.

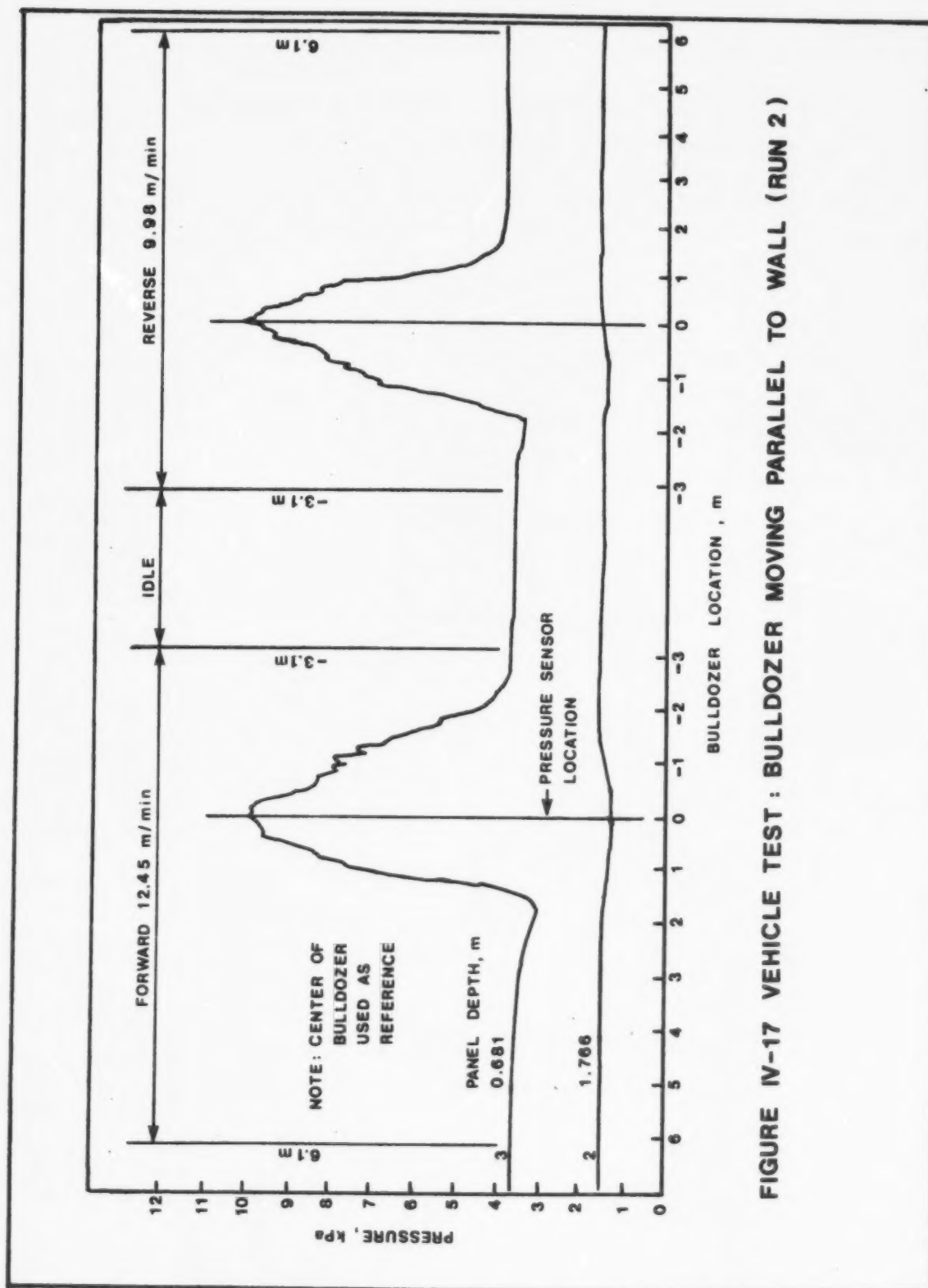


FIGURE IV-17 VEHICLE TEST : BULLDOZER MOVING PARALLEL TO WALL (RUN 2)

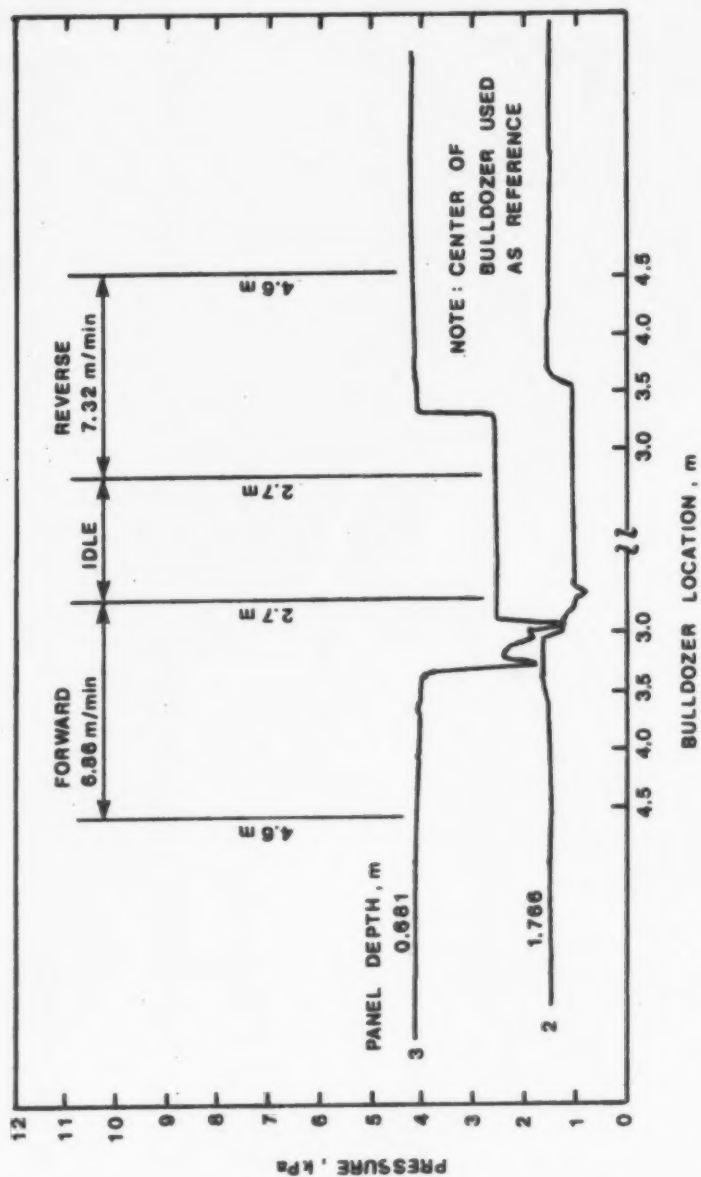


FIGURE IV-18 VEHICLE TEST: BULLDOZER MOVING PERPENDICULAR TO WALL (RUN 5). BLADE LOWERED.

4. Motion Perpendicular to Wall - Blade Up

Runs 10 to 13 were a repeat of Runs 5 to 7, except with the blade in the fully-raised position. This allowed the center of the bulldozer to come within 1.4 m of the wall. A typical result from these series of tests is given in Figure IV-19.

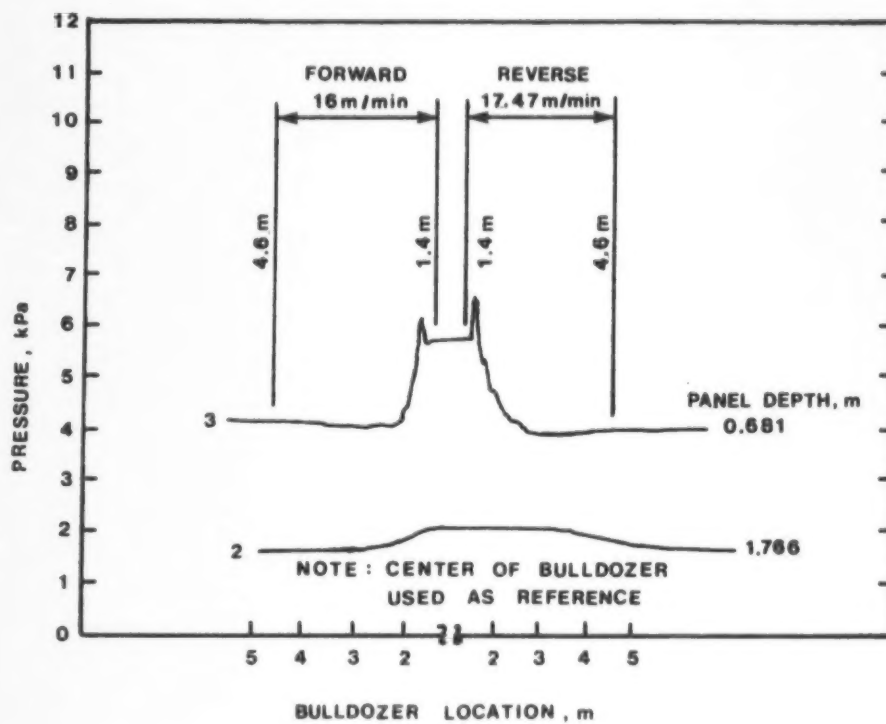


FIGURE IV-19 VEHICLE TEST: BULLDOZER MOVING PERPENDICULAR TO WALL AT PRESSURE SENSOR (RUN 12). BLADE RAISED.

V. ANALYSIS AND INTERPRETATION OF TEST DATA

This chapter presents analyses of all the test data gathered in Phases I and II. The methods of analysis and type of presentation were chosen to produce design factors compatible with procedures that are presently used for the design of retaining walls. The inter-relationships of the variables that are used in this chapter to present most of the data are explained in Chapter II, Theoretical Background.

A. Effect of Pile Height, Pile Shape, and Material Characteristics On Pressure

1. Initial Pile Build-Up

Data for pile build-up against a bare wall were obtained during three tests with green chips at Canfor and two tests with hog fuel at Fraser Mills. Two other tests with hog fuel at Fraser Mills gave data for pile build-up on top of a wedge-shaped dormant pile unreclaimed from against the wall. All of these tests are analyzed in this section, while the results for Fraser Mills showing the pressure increase that had occurred two or three days after the pile had reached near its full height are presented in the next section.

The relationships between material height and pressure for green chips are shown in Figure V-1 for the three pressure sensors. Pressure in this plot has been normalized by dividing by the packed green density measured in the laboratory. Normalized pressure compensates for natural fluctuations of wood density and moisture content. Average pile slopes were quite consistent for the three test runs varying only from 28.44° to 32.18° ; pile slope increased during the tests from about 20° to as high as 48° . The pressure responses for the panels placed at three different depths show that pressure does not vary linearly with height of material, and is dependent on pile size. According to simple theory, all the results in this figure should have followed the same curve. The dependence of pressure build-up on pile size makes accurate prediction of the thrust on a retaining wall for a pile shape and pile dimensions different than those tested for Canfor, a difficult task, since there are insufficient data to generalize the measured results with much confidence.

The reduction in the incremental increase in pressure for each incremental increase in pile height as the pile height increases is consistent with the results of Symons and Wilson (1972), and Wroth (1972). The measured effect of location on the wall is also in general agreement with what has been observed in these previous studies.

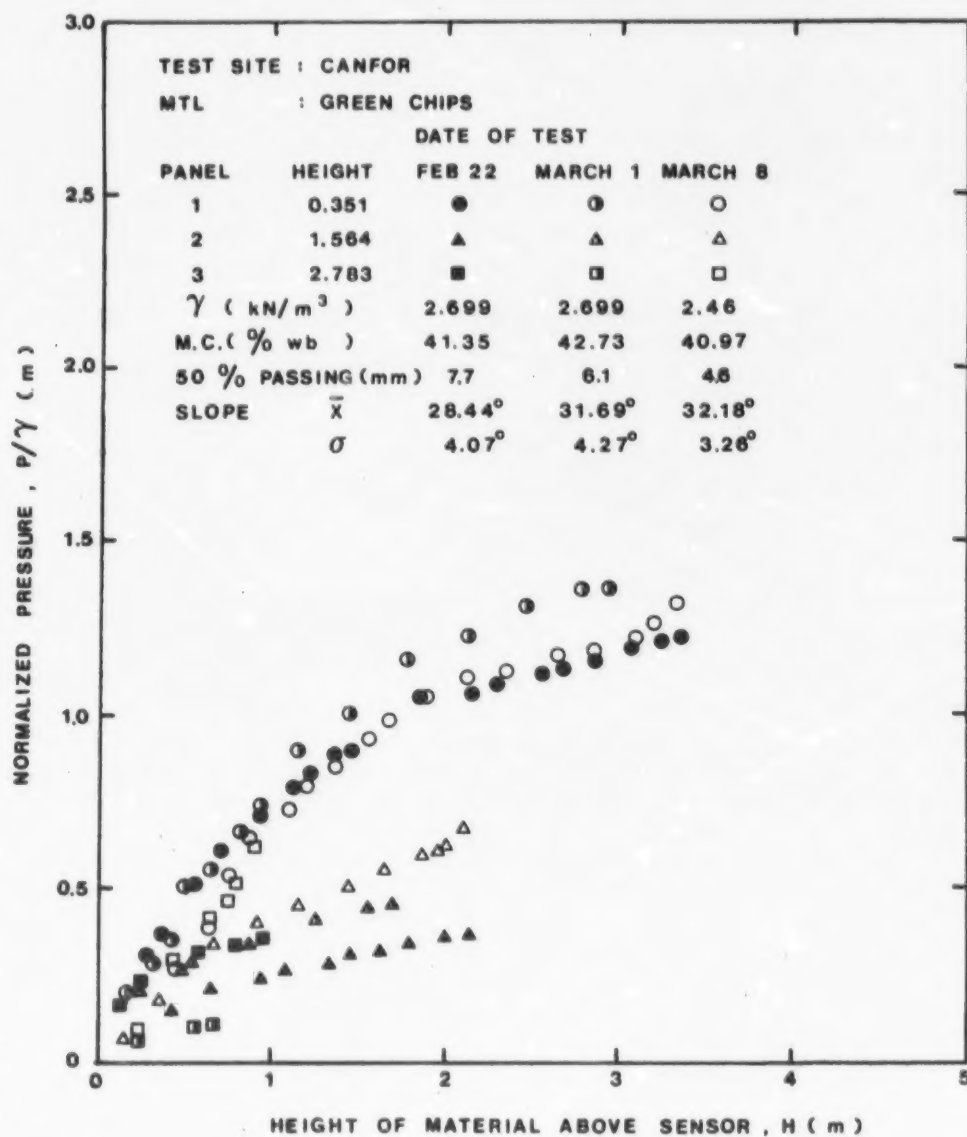


FIGURE V-1. HORIZONTAL PRESSURE IMPOSED BY GREEN CHIPS AT CANFOR

The most consistent results are those for the bottom pressure sensor. Scatter of the pressure data increases as the depth of the sensor decreases.

Figure V-2 gives values of the coefficient of active horizontal pressure calculated from results for green chips. The curve for the 0.351 m sensor gives the average of the three tests, all data being within 15% of the average values. The fit for the 1.564 m sensor is much poorer, all data being within about 35% of the average values. No reasonable fit could be made for the sensor at 2.783 m.

Fitting a semi-logarithmic relationship as discussed by Wroth (1972) to the k_{ah} Curve for the bottom panels gives the equation:

$$k_{ah} = 0.76 - 0.311 \ln H$$

This relationship fits the data very well when the height of material above the sensor falls between 0.45 m and 3.3 m.

The values measured for k_{ah} were compared to values predicted by the Coulomb equation for horizontal pressure on a wall with friction. Using a friction angle of 27° , based on the measured value for hog fuel on stainless steel, and a pile slope of 31° , a k_{ah} of 0.4, as was measured for a height of material of 3.1 m, requires an internal friction angle of 37.5° . This angle is only 19% greater than the average of the measured angles of repose.

The pressure on the retaining wall was found to vary non-linearly with increasing depth (Figure V-3). For two of the three test runs at the chip site, the final pressures at Panels 2 and 3 were equal, a result attributed to the erratic behaviour of the pressure at shallow depths. The pressure distribution during build-up on March 1 was linear until the pile height at the wall reached near 2 m, after which the interrelationship became increasingly non-linear. The magnitude and location of the resultant thrust on the wall based on measured pressures and a uniform distribution per unit width are summarized in Table V-1. For comparison, magnitudes and locations of thrusts for the three runs assuming a linear increase of pressure to the maximum registered value transposed to ground level are also given. The magnitude and location of the actual thrust are within 15% of those for ideal conditions.

Five test runs were made with hog fuel at Fraser Mills, four being with a single pressure sensor at a height of 0.77 m above the floor, and one being for Phase II with three pressure sensors. Results from all but the first run in Phase I (November 23, December 2, and December 14) and for the May 4 run in Phase II are shown in Figure V-4 in terms of the normalized pressure. The variable H used to plot data for build-up on top of the dormant

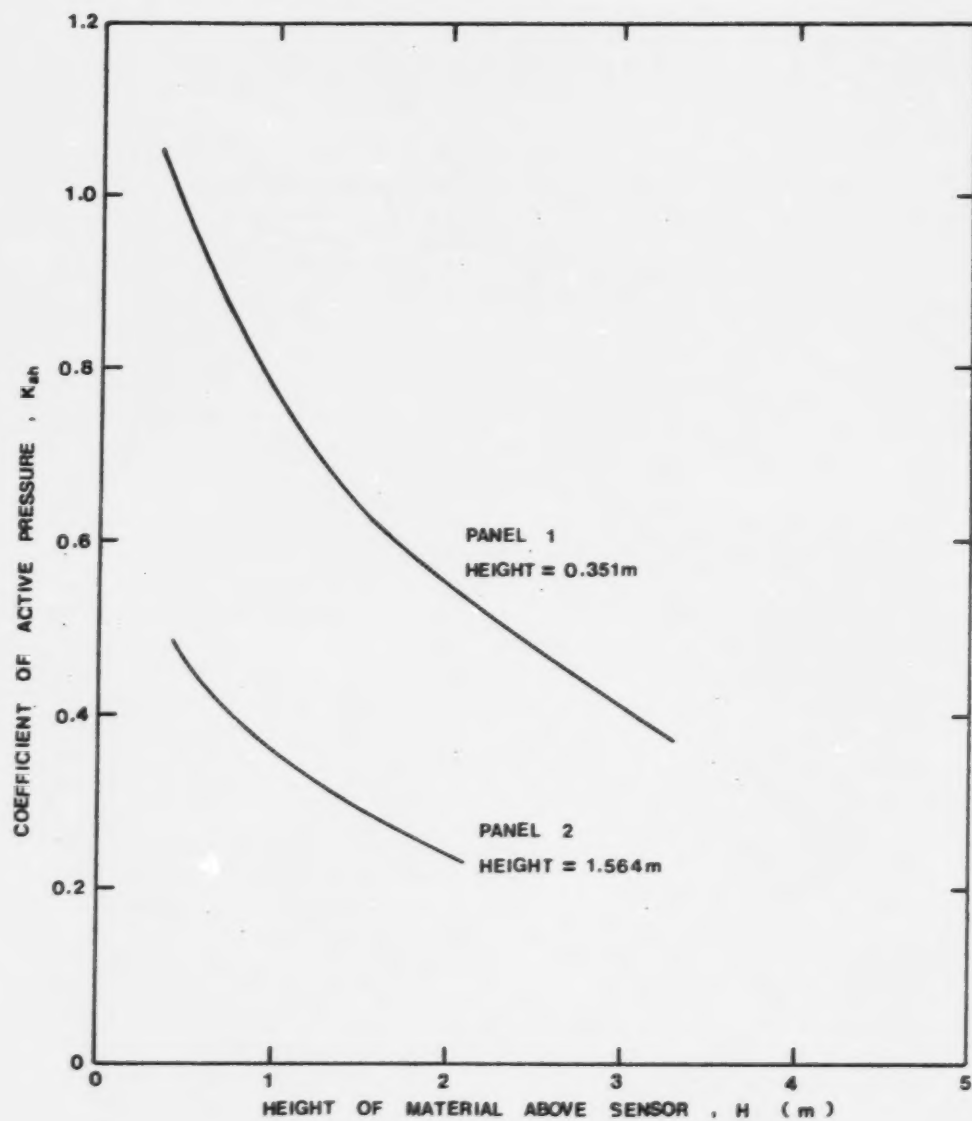


FIGURE V-2 COEFFICIENT OF ACTIVE HORIZONTAL PRESSURE FOR CHIPS AT CANFOR (AVERAGE OF ALL TESTS)

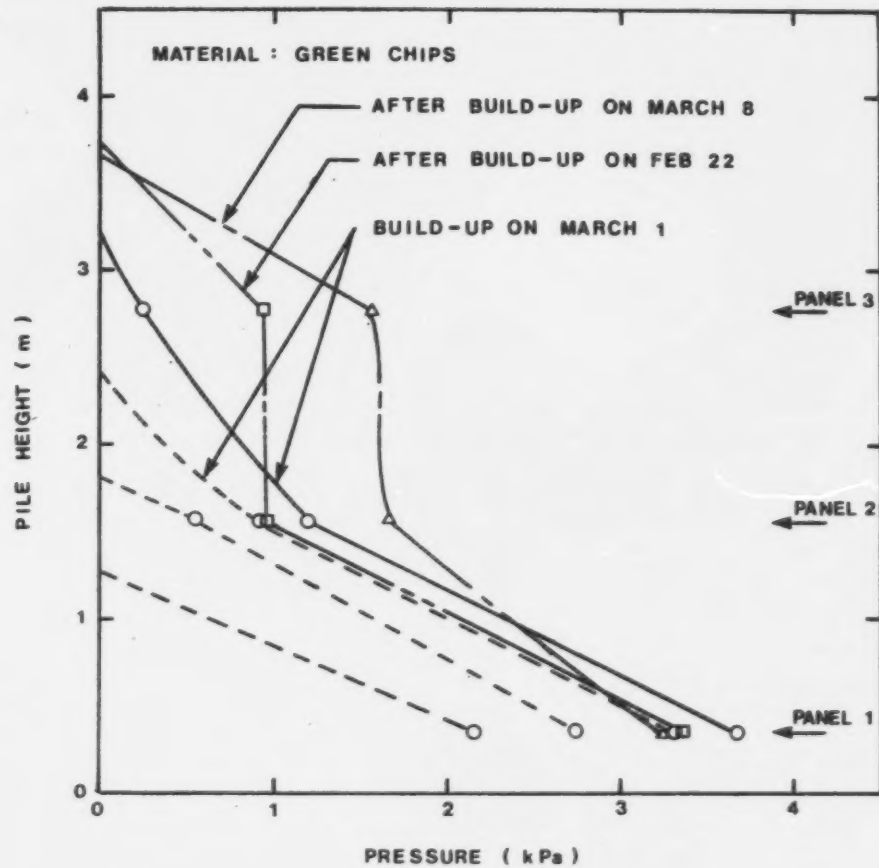


FIGURE V-3 DISTRIBUTION OF THE PRESSURE IMPOSED BY GREEN CHIPS AT CANFOR

Table V-1

MAGNITUDE AND LOCATION OF RESULTANT THRUST ON
CHIP PILE RETAINING WALL

RUN	PILE HEIGHT AT WALL (m)	THRUST		HEIGHT OF THRUST RESULTANT	
		ACTUAL ^a (kN/m)	IDEAL ^b (kN/m)	ACTUAL ^a (m)	IDEAL ^b (m)
Feb. 22	3.72	5.33	6.17	1.17	1.24
Mar. 1	3.26	5.29	6.0	0.95	1.09
Mar. 8	3.66	6.70	5.88	1.37	1.22

^a Assumes constant pressure below Panel 1.

^b Ideal case when pressure increases linearly with distance below surface.

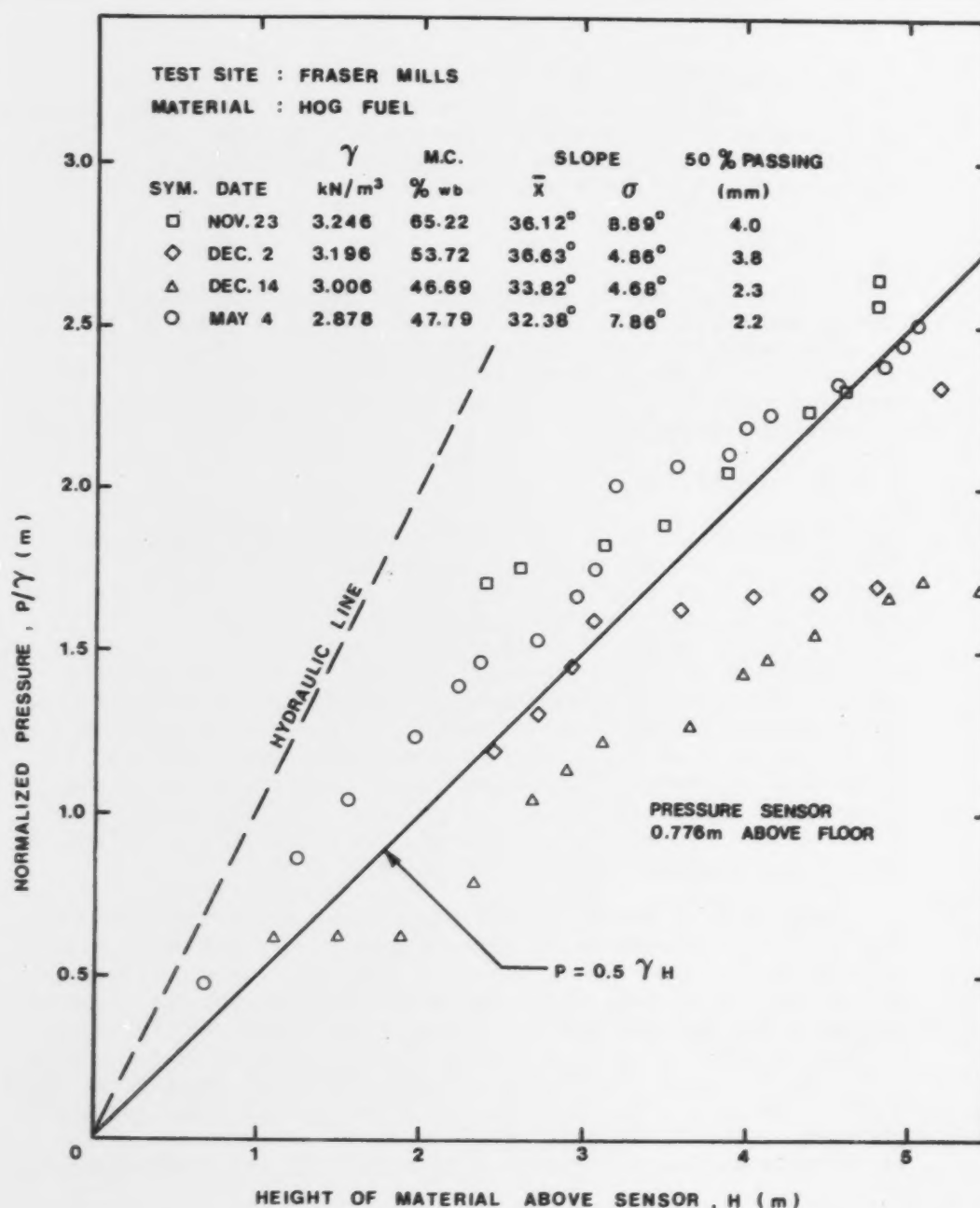


FIGURE V-4 HORIZONTAL PRESSURE IMPOSED AT
BOTTOM PANEL BY HOG FUEL AT
FRASER MILLS

piles present at the start of the tests on November 23 and December 2 was set equal to the height of the intersection between an extension of the pile slope and the wall surface, until the pile height at the wall exceeded the height of the dormant pile. An approximate fit to these data is shown:

$$P = 0.5 \gamma H.$$

This result may be compared to the theoretical result predicted by the Coulomb equation with an average pile slope of 35° and an experimentally-determined wall friction angle of about 27° (Appendix IV). Assuming the internal friction angle equals the measured angle of repose, the theoretical relationship for horizontal pressure becomes,

$$P = 0.67 \gamma H.$$

An increase of the internal friction angle to 36.2° reduces k_{ah} from 0.67 to 0.5, the value estimated from the field data. Laboratory tests of two samples of hog fuel, one from Fraser Mills, the other from Canfor, resulted in values for the internal friction angle of 59.4° and 57.5° , respectively (Appendix IV). Both samples were screened to remove particles over 2.5 cm in size prior to testing and, therefore, may not apply to the hog fuel used in the field tests. With this qualification, it is still evident that use of values for ϕ on the order of the measured ones would lead to prediction of erroneously low horizontal wall pressures by the theoretical relationship. k_{ah} at an internal friction angle of 59° , and with the wall friction angle and pile slope as before is only 0.08; far below the measured value of 0.5.

Results from the three wall panels used May 4 for tests with hog fuel at Fraser Mills are presented in Figure V-5 along with a plot of the range of values measured with the bottom pressure sensor at the Canfor chip pile. The difference between the shape of the curve for hog fuel and for chips is attributed mainly to the difference between the pile shapes. As was observed for the chip pile, the response of wall pressure to pile height depends on location on the wall. The cause of the higher pressure for the middle pressure sensor at the same height of material above the sensor is believed to be due to peculiarities of the bin and loading method.

For design purposes, the values for k_{ah} from the May 4 hog fuel test are presented in Figure V-6. k_{ah} at the 0.776 m high sensor approached a value of 0.5 at maximum pile height, which is the same as the value plotted previously to fit all the data for this sensor. The decrease of k_{ah} with increased pile height is comparable to the behaviour observed for the chip pile, although the effect of sensor height is unusual. Correlation of the dependence of k_{ah} on sensor location would require further testing.

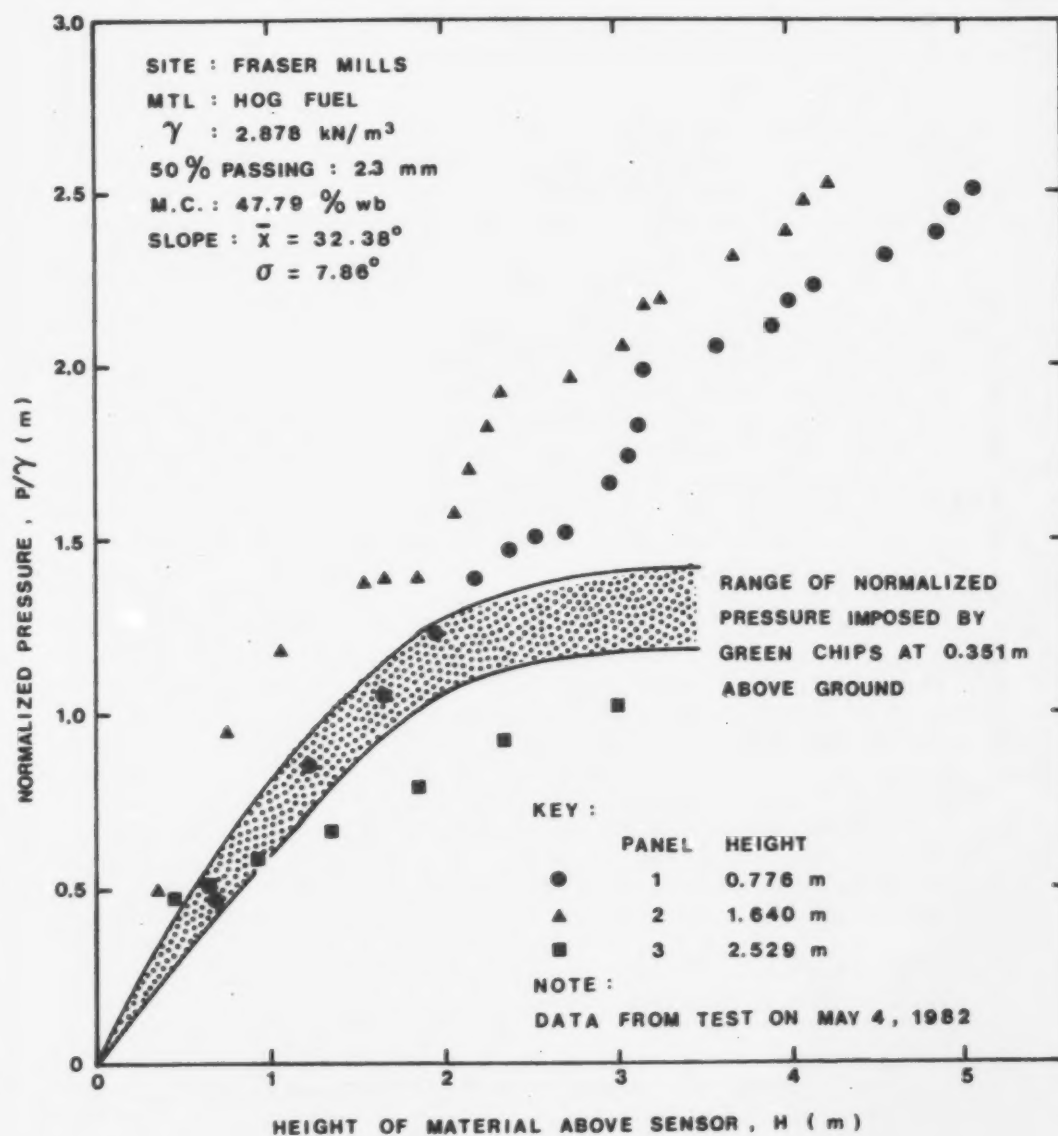


FIGURE V-5 HORIZONTAL PRESSURE IMPOSED BY HOG FUEL AT FRASER MILLS

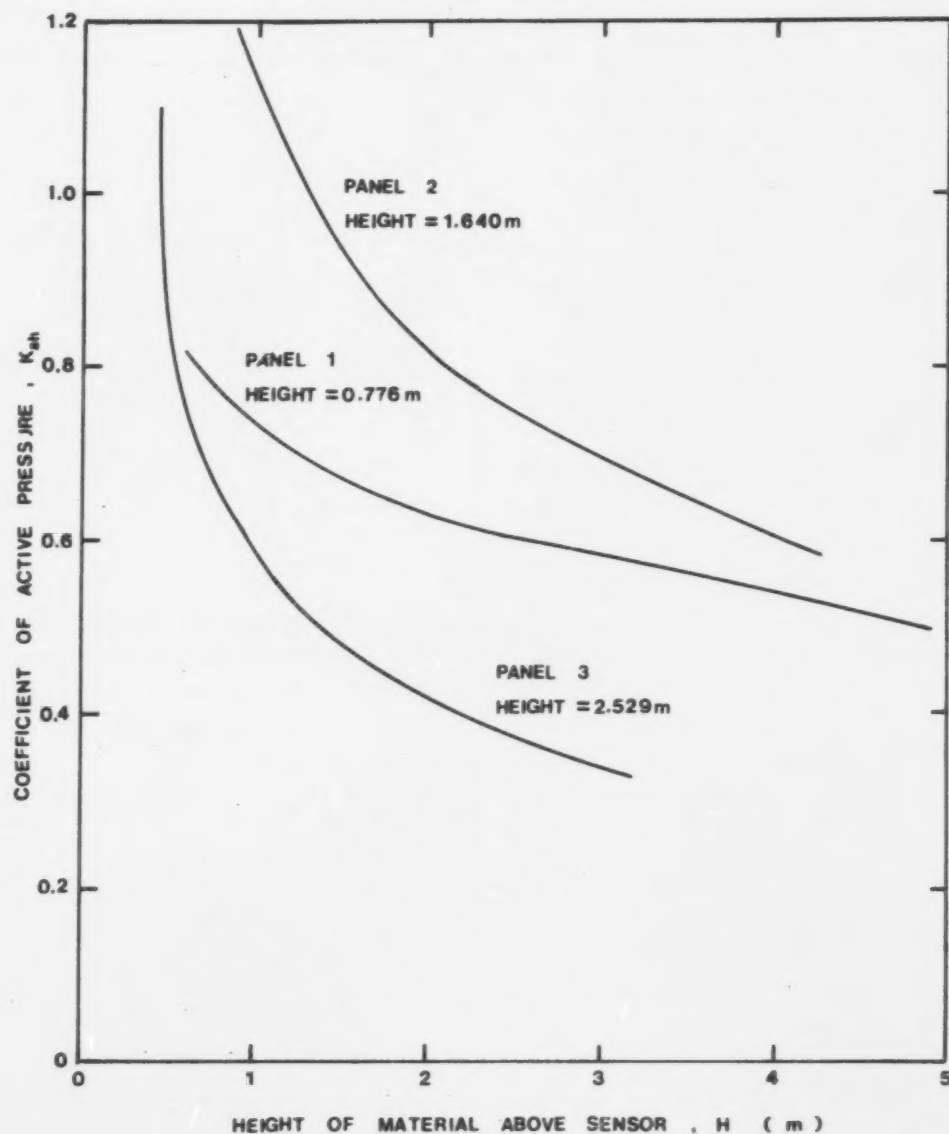


FIGURE V-6 COEFFICIENT OF ACTIVE HORIZONTAL PRESSURE FOR HOG FUEL AT FRASER MILLS (MAY 4)

Fitting a semi-logarithmic relationship to the results for k_{ah} at the 0.776 m high sensor gives the following:

$$k_{ah} = 0.735 - 0.15 \ln H.$$

All results obtained for pressures at the bottom sensors of the chip and hog fuel piles built-up against bare walls are summarized in Figure V-7. For pile heights up to about 0.5 m, the pressure developed on the wall was equal to that for a fluid of the same bulk density. Beyond this height, k_{ah} reduces from 1.0 to near the 0.5 value previously determined.

Pressures developed on May 4 and for several weeks following were monitored (Figure V-8). It is evident from this plot that the pressure distribution on the wall is affected by the number of loading cycles. No material was removed from against the wall prior to any but the first build-up, so dormant piles much like observed during Phase I were present. By the third build-up, pressures appeared to have stabilized to near the final values approximated by those following the ninth build-up.

The pressure distribution observed for the Fraser Mills site has the same general form as that for the chip pile at Canfor. The maximum total thrust on the wall was present following the first build-up and after the pile had filled the bin, making the pile surface two-dimensional in shape. An analysis of the results in Figure V-7 measured after the first build-up shows the thrust to be 29.3 kN/m, and the height of the center of effort to be 1.9 m. Assuming a linear pressure distribution over the full 6.3 m pile height with a maximum pressure equal to the result at Panel 1, the thrust is 34.6 kN/m, acting at a height of 2.1 m. Consequently, the assumed ideal conditions lead to an over estimation of thrust by 18% and an over estimation of the height to the center of effort by 11%.

2. Pressure Rise After Initial Pile Build-Up at Fraser Mills

Previously in Figure V-4 of Section 1, the results were shown for the distribution of pressure during pile build-up at Fraser Mills. Significant, though not consistent differences in pressure were observed between results for the initial pile buildup and for the end of the week. A summary of these results is given in Table V-2. The average of k_{ah} for the initial pile build-up is 0.44, while the average for the end of the week, up to and including the result for May 7, is 0.49; a value close to the previous estimate of 0.5 shown in Figure V-4. The probable cause of the difference between pressures after initial build-up and at the end of the week is the difference in the shape of the pile. After initial build-up, the leading face of the pile was shaped at a natural angle of repose, while the pile in front of the sensors was two-dimensional in shape by the end of the week.

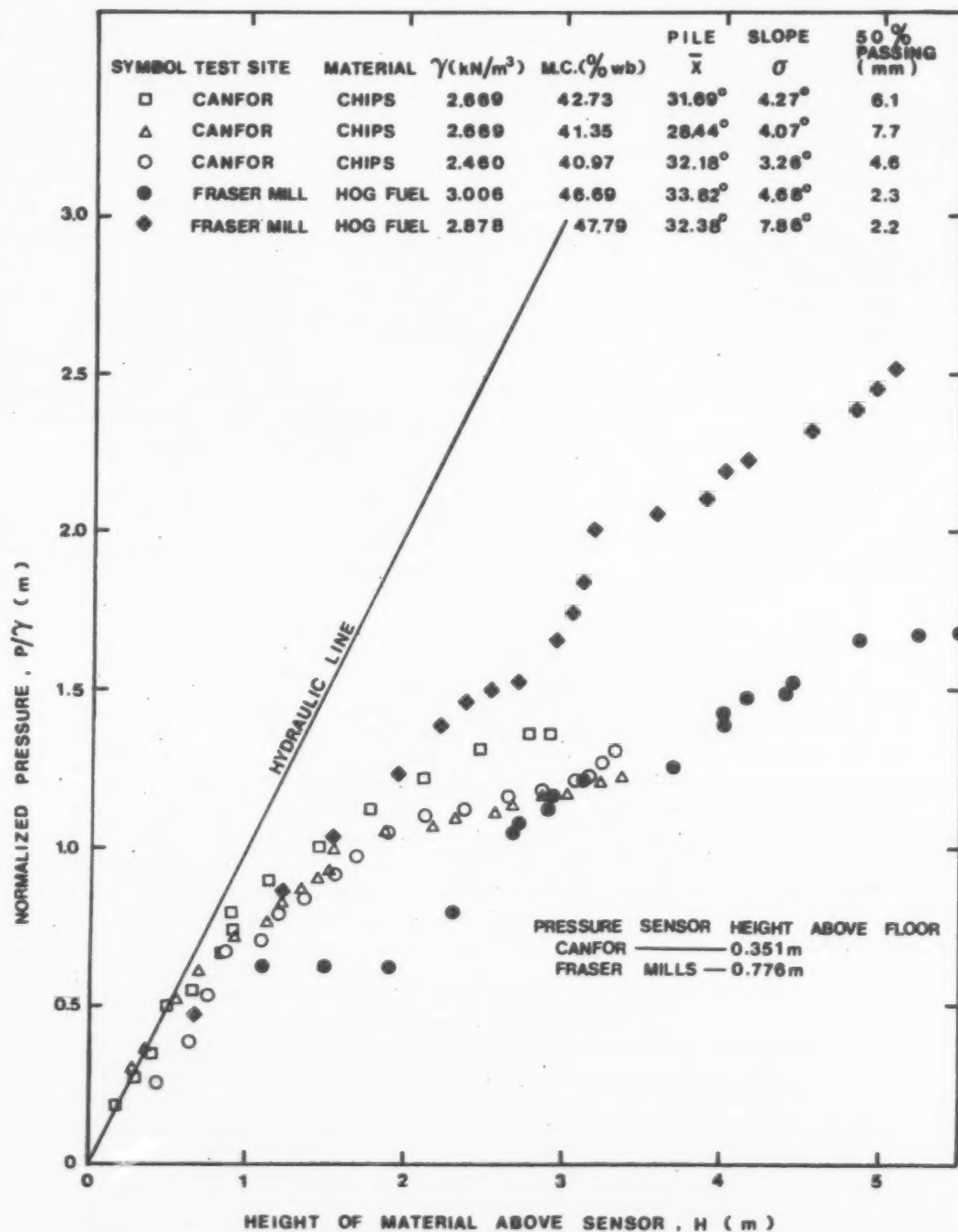


FIGURE V-7 HORIZONTAL PRESSURE IMPOSED AT BOTTOM PANELS BY CHIPS AND HOG FUEL UPON BARE WALL

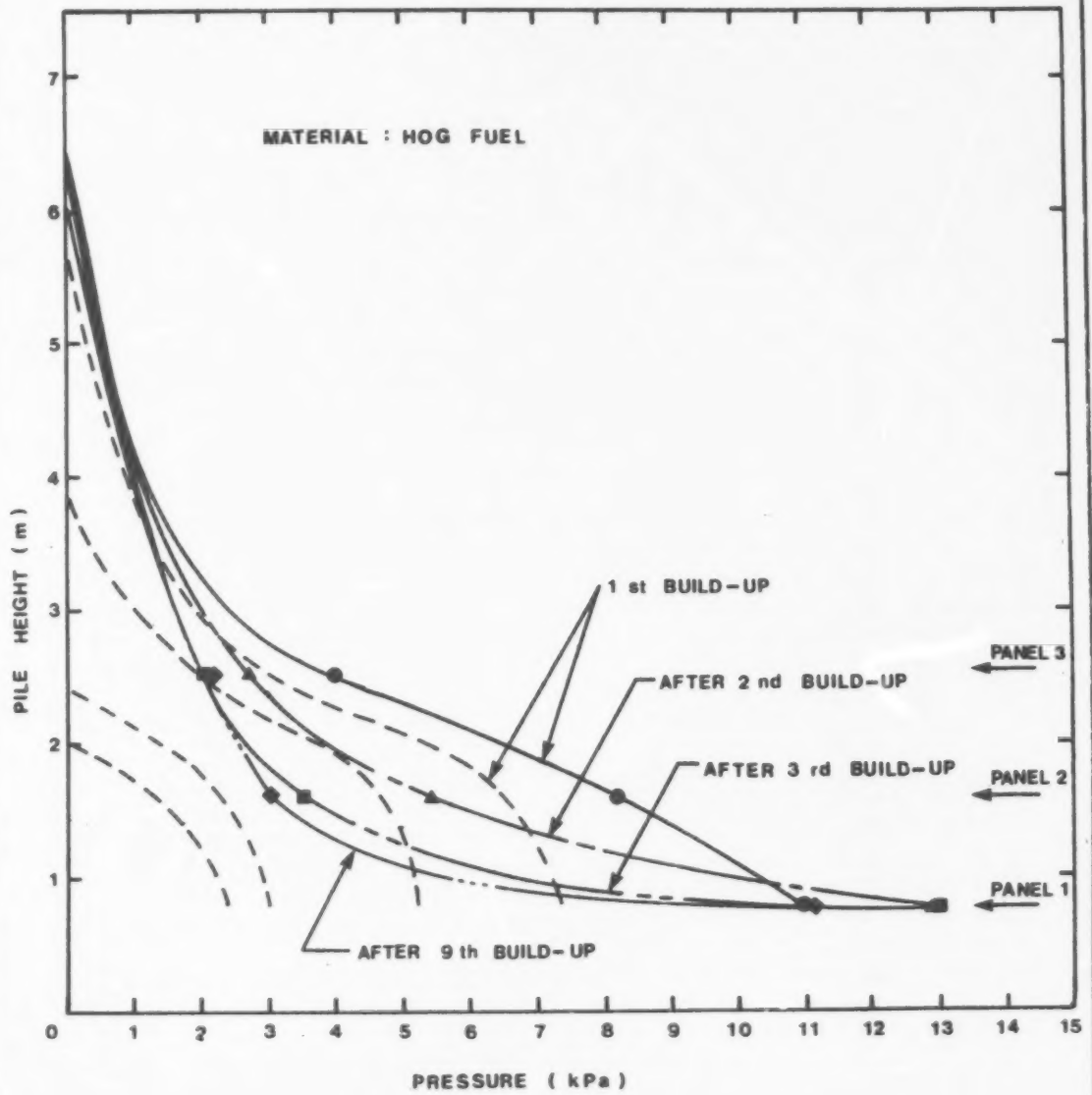


FIGURE V-8 DISTRIBUTION OF THE PRESSURE IMPOSED BY HOG FUEL AT FRASER MILLS

Table V-2

PRESSURES AT FRASER MILLS IMMEDIATELY AFTER BUILD-UP AND
AT THE END OF THE WEEK OF THE TEST

TIME/DATE	INITIAL BUILD-UP			END OF THE WEEK			k_{ah} AT AT END OF WEEK
	HEIGHT ABOVE SENSOR (m)	ANGLE OF REPOSE (°)	PRESSURE AT PANEL 1 (kPa)	HEIGHT ABOVE SENSOR (m)	ANGLE OF REPOSE (°)	PRESSURE AT PANEL 1 (kPa)	
1250/Nov. 24	4.80	47.6	8.63	5.79	39.7	9.28	0.49
1510/Dec. 2	5.21	43.3	5.69	5.21	41.4	7.44	0.45
1350/Dec. 15	5.59	39.2	5.20	5.64	38.8	7.14	0.42
1345/May 5	6.30	44.3	10.30	6.35	44.3	10.99	0.60
				6.24	42.7	13.05	0.73
				6.45	40.2	13.07	0.70
				6.15	40.8	11.08	0.63
				AVERAGE			0.44

The value of k_{ah} was affected by cyclic build-up of the pile, increasing from 0.60 to as high as 0.73. Some of the observed difference may be due to an unrecorded variation of the material density, since the calculation of k_{ah} for all results on and after May 4 use the same material density of 2.878 kN/m^3 . The maximum k_{ah} shown could be reduced to its original value by an increase in the packed material density to 3.50 kN/m^3 . Since this is higher than all material densities that were measured during the tests with hog fuel, some of the change in wall pressure is believed due to an increase in the density of dormant material by compaction and an alteration of the stress distribution near the wall by changes in the mechanical properties of the residues.

The results for the pressure distribution on the wall during build-up indicate it is time-dependent; pressures at the base of the wall increased, while pressures on the upper part of the wall decreased. The pressure distribution appeared to have nearly stabilized after the third build-up.

The average slope of the pile for all data obtained when the bin was full at the end of the week is 41° . Assuming the internal friction angle is equal to the angle of repose at the surface gives a theoretical k_{ah} of 0.57 when $\theta = 27^\circ$; a value in the upper part of the range of k_{ah} (0.42 to 0.60) for the data recorded at the end of the week for each test.

3. Floor Pressure at Fraser Mills

Results for pressures sensed by a load panel placed on the floor of the bin at Fraser Mills with the center point of the panel 0.387 m from the wall are summarized in Table V-3. This panel was of the same size and design as the units mounted on the bin wall. The pressures indicated by the panel were resolved into vertical and horizontal components using the measured floor slope.

It is evident from the data that the floor pressure near the location of the sensor was strongly influenced by the presence of the wall and the existence of wall friction. This effect was observed to decrease with time, and the pressure consequently approached the maximum equal to γH . After the ninth build-up, the floor pressure had approached near 0.8 of the expected maximum value.

The ratio of horizontal to vertical pressure based on data from Panel 1 and the floor panel varied from 3.5 on May 7 to 0.77 on July 2. These values were determined using the pile heights appropriate to each panel and, therefore, are not ratios of horizontal to vertical pressure at the same pile height. Even so, this ratio serves to emphasize the boundary effects of the floor and wall close to the corner of the bin.

Table V-3
FLOOR PRESSURE MEASURED AT FRASER MILLS
0.387 m FROM THE BIN WALL

TIME/DATE	HEIGHT ABOVE SENSOR (m)	VERTICAL PRESSURE, P (kPa)	$\frac{P}{\gamma H}$ *
1545 May 4	4.14	2.84	0.24
1720 May 4	5.38	2.92	0.19
1800 May 4	6.01	3.06	0.18
1345 May 5	6.43	3.1	0.17
1400 May 7	6.57	3.12	0.165
1415 May 14	6.48	5.3	0.28
1400 May 21	6.64	10.06	0.53
1430 July 2	6.22	14.33	0.80

* The packed bulk density, γ , was 2.878 kN/m^3 for a sample taken on May 4.

B. Effect of Pile Age on Pressure

At the start of the age test, hog fuel was piled to a height of 2.77 m above the pressure sensor. The coefficient of active horizontal pressure at this time was 0.38 based on the measured average bulk density of packed material. Although the pile height remained constant, the pressure at the sensor decreased to give a k_{ah} of 0.33 on February 5, three days after the start of the test. While filling valleys present in the vicinity of the sensor on the surface of the pile, the pressure increased but pile height remained approximately constant. On February 12 after the change of the pile surface, k_{ah} increased to 0.37, assuming the bulk density of the material was as measured at the start of the test.

Because of variation in the weather, the moisture content and, thus, the density of the hog fuel samples taken from the surface varied substantially. Since the wall pressures did not vary correspondingly, it appears that density fluctuations were limited to a relatively shallow depth, and the most influential part of the pile retained near its original density.

The theoretical value of k_{ah} for a flat pile with an internal friction angle of 41° and a wall friction angle of 27° is 0.17 according to the Coulomb equation. This is near one-half of the measured value, and this relationship, therefore, gives a much poorer estimate of pressure for flat piles than for sloping piles such as those monitored during other tests.

C. Effect of Vehicle Traffic on Pressure

1. Movement on Top of a Pile

A summary of the results from the four runs at Canfor in which the vehicle was moved parallel to the wall at constant velocity in forward and reverse directions is presented in Figure V-9. The pressure response at the first sensor below surface (Panel 3) was repeatable and showed some pressure decrease as the vehicle approached and departed from the vicinity of the sensors. The magnitude of the pressure drop before and after the pressure peak decreased with each run. The greatest measured pressure rise occurred at Panel 3 and amounted to 6.36 kPa (Table V-4). Pressure changes measured at Panel 2 varied from a decrease of 0.5 kPa to an increase of 0.2 kPa and did not correlate with the pressure changes observed at Panel 3.

Theoretical pressure increases due to the presence of a vehicle were calculated using two simple models. One model assumed the presence of two parallel line loads of infinite length located at the centerline of each track 0.725 m and 2.075 m away from the wall. The other model assumed two point loads with a total

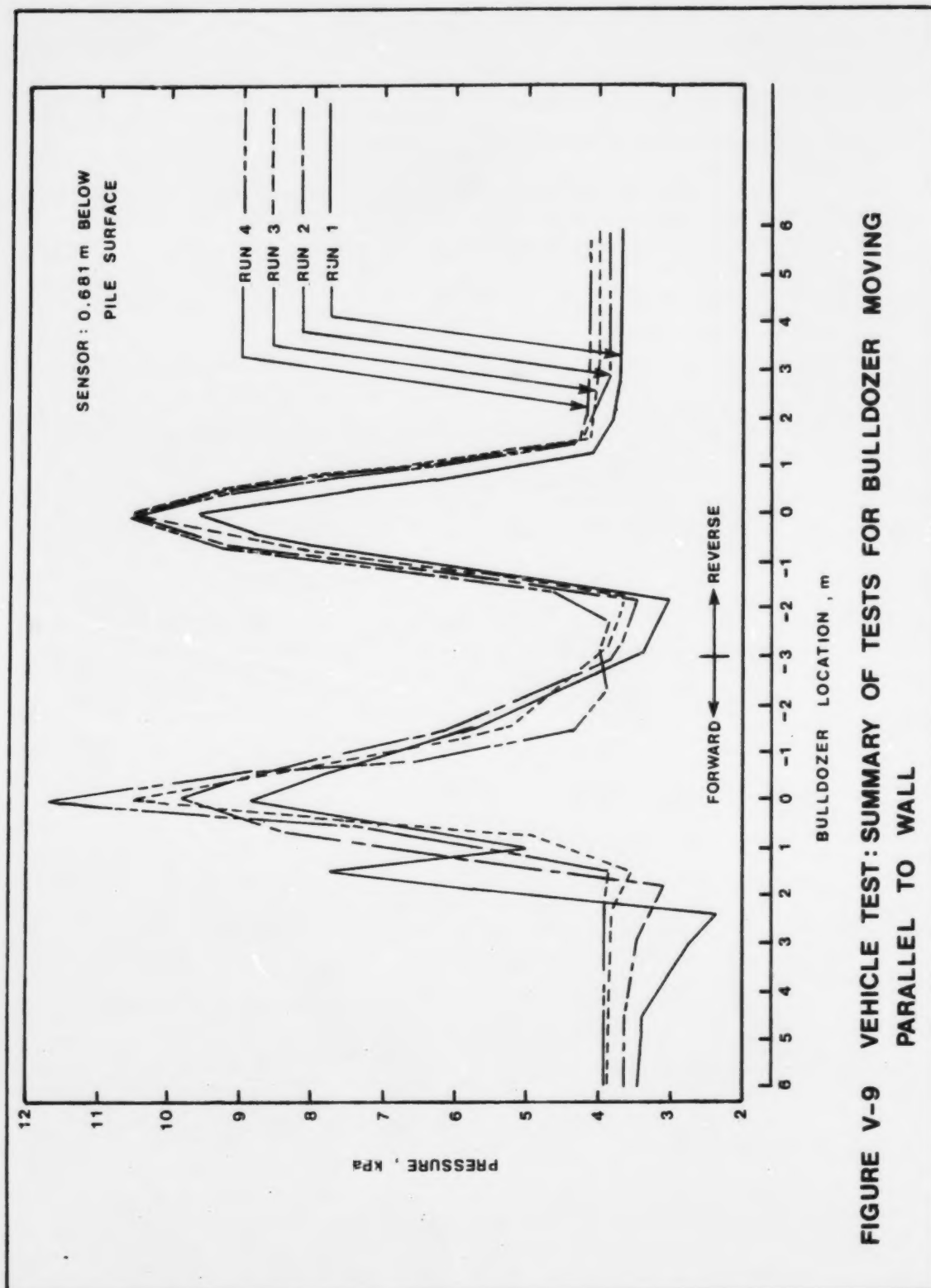


Table V-4

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS
FOR LATERAL PRESSURE RISE
DUE TO THE VEHICLE POSITIONED PARALLEL TO THE WALL

LOCATION	HEIGHT ABOVE GROUND (m)	DEPTH (m)	MAXIMUM PRESSURE RISE (kPa)			
			EXPERIMENTAL ^a		LINE LOADS ^b	POINT LOADS ^c
			MEAN	STD DEVIATION		
Panel 3	2.869	0.681	6.36	0.63	6.30	5.36
Panel 2	1.784	1.766	0		4.78	5.11
Panel 1	0.703	2.847	0		2.37	2.19
Maximum	---	0.92			6.65	--
Pressure		1.10			--	6.76

^a Data for four runs (8 passes) parallel to wall.

^b Empirical formula assuming two line loads of 13.93 kN/m located at centerlines of tracks (Appendix V).

^c Empirical formula assuming two point loads of 37.16 kN located in front of sensors at centerlines of tracks (Appendix V).

magnitude equal to the vehicle weight located at the center of each track area immediately in front of the sensors. These calculations (Appendix V) indicate that the closest estimate of the pressure at Panel 3 is given by the line-load model. Both models give very poor estimates of pressures at Panels 1 and 2, indicating the pressure due to the vehicle does not penetrate as deeply in wood residues as in soils and granular solids for which the empirical relationships were developed.

On average, a pressure increase occurred when the vehicle reached a point 5.9 m before the sensors, and a return to the base pressure occurred after the vehicle had reached a point 7.4 m past the sensors. Assuming the depth of penetration of the pressure rise was at Panel 2, the total wall area enduring the effect of elevated pressure was about 8.4 m^2 .

Two runs (Runs 8 and 9) were made with the vehicle moving parallel to the wall and stopping at certain locations for pressure readings. The maximum pressure rise at Panel 3 had a mean of 5.42 kPa and a standard deviation of 0.94 kPa. The mean value is 15% below the comparable result for continuous vehicle movement, although such a difference is attributed to experimental error and slight variations in the vehicle location. Three runs were done at a vehicle speed of 9.1 to 12.5 m/min. One run done at a vehicle speed of 30 m/min gave results similar to those obtained at the slower speeds indicating that vehicle speed does not significantly influence the pressure rise on the wall when movement is parallel to the wall.

A comparison of experimental and theoretical results for movement of the bulldozer perpendicular to the wall (blade up) is given in Table V-5. The theoretical results calculated assuming two point loads, one at the center of each track 1.64 m from the pressure sensors and at an angle to the wall of 65.8° , are only similar to the experimental findings for Panel 3.

The pressure rise at the sensors began when the center of the vehicle reached 1.8 m from the wall and had achieved its maximum value when the center of the vehicle reached 1.5 m from the wall.

The drop in pressure at the wall for the test runs done with the bulldozer moving perpendicular to the wall with the blade down are not consistent with other data measured for similar conditions and cannot be explained.

Pressure distributions are given in Figure V-10 for prior to any vehicle movement on top of the pile, for the maximum recorded pressure at Panel 3 for vehicle movement parallel to the wall, for immediately after completion of the last test run, and for the sixth day after completing the tests. The results for immediately after the tests are essentially identical to those obtained after

Table V-5

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS
FOR LATERAL PRESSURE RISE
DUE TO THE VEHICLE POSITIONED PERPENDICULAR TO THE WALL

LOCATION	HEIGHT ABOVE GROUND (m)	DEPTH (m)	VEHICLE POSITION (m)	PRESSURE RISE (kPa)		
				EXPERIMENTAL ^a		POINT LOADS ^b
				MEAN	STD DEVIATION	
Panel 3	2.869	0.681	1.5	2.48	0.195	2.71
Panel 2	1.784	1.766	1.5	0.298	0.075	5.06
Panel 1	0.703	2.847	1.5	0	0	2.04

^a Data for four runs (8 passes) parallel to wall.

^b Empirical formula assuming two point loads of 37.16 kN located at center of tracks. Loads located 1.64 m from sensors at 65.8° from wall.

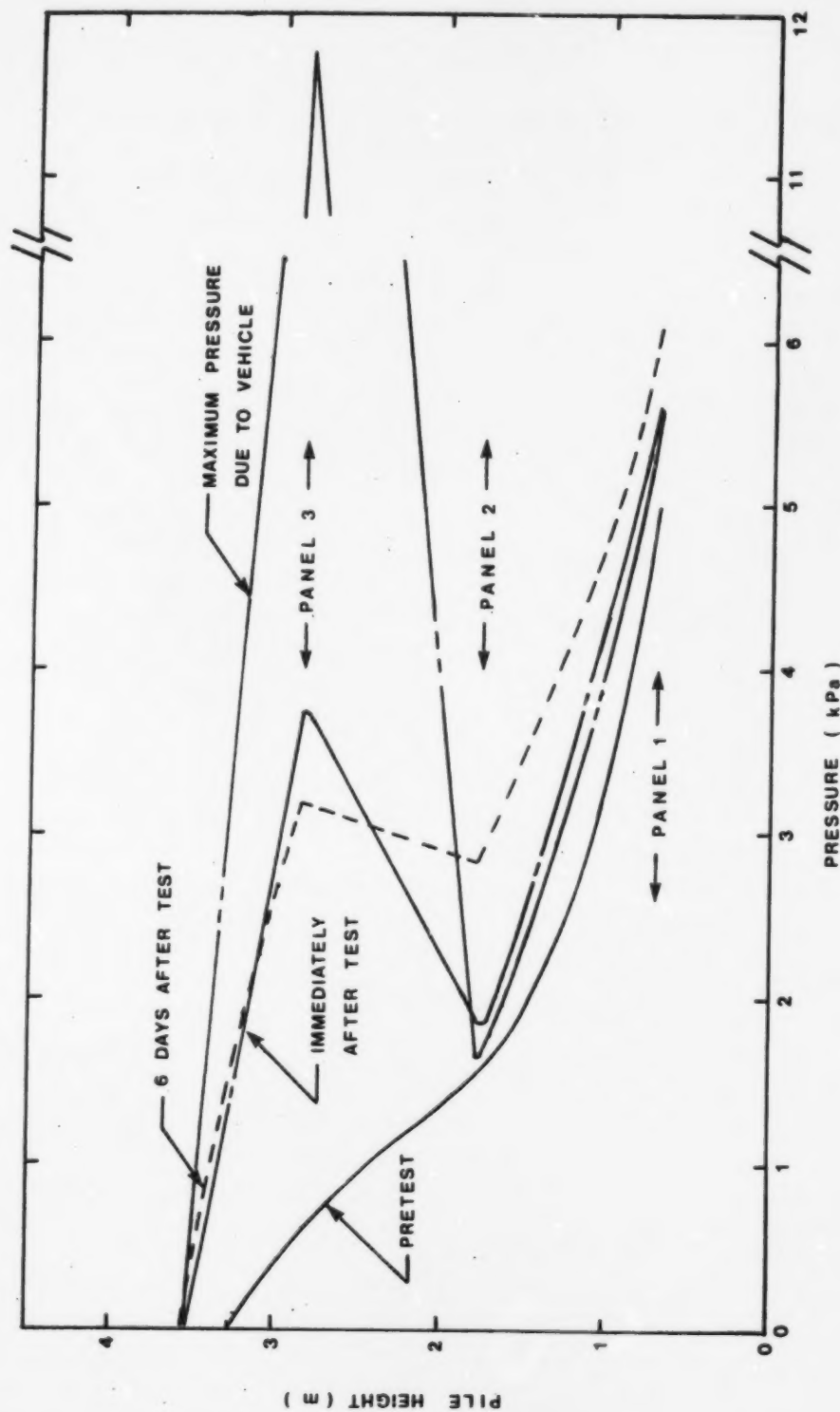


FIGURE V-10 DISTRIBUTION OF HORIZONTAL PRESSURE BEFORE, DURING AND AFTER THE PASSAGE OF THE VEHICLE PARALLEL TO THE WALL

initial leveling and compaction of the pile. Results for the sixth day after the tests indicate that some diffusion of the pressure produced by compaction occurs with time. The k_{ah} for Panels 1, 2, and 3 prior to any vehicle traffic on the pile were 0.40, 0.24, and 0.31 respectively. The value for Panel 3 is greater than that measured at the start of the age test (0.38).

2. Reclaiming From the Base of a Pile

After completion of one test run at the Canfor chip pile during which pressures and pile heights were monitored, the effect of reclaiming chips from the side of the pile opposite the wall was investigated. At the time of the test, the pile had a conical shape with a base diameter of 11.6 m and a height of about 9.1 m at a distance 3.6 m from the wall. A loader was used to reclaim three bucket loads at ground level from an area about 9.4 m from the wall. Filling the loader bucket was accomplished by pushing toward the wall.

For the three buckets that were recovered, a negligible transient increase in pressure occurred at Panels 1 and 2.

D. Sensitivity of Pressure to Panel Deflection

Tests were conducted to investigate the elasticity of wood residues by adding different weights to the back of the load panel. These tests were done using the three panels installed on the hog fuel bin at Fraser Mills at a time when the bin was full.

The test results are summarized in Figure V-11. Pressure decreased linearly over most of the investigated range of counterweights, indicating the hog fuel behaved like an elastic solid. The pressure response at Panel 1 shows a loss of linearity at higher counterweights and, thus, higher panel deflections which is expected for bulk solids such as wood residues. The decrease in pressure with panel deflection under load is somewhat surprising considering the small deflection involved, but is consistent for all three panels. The deflection of the load cells as a function of load was not measured in this study precluding the determination of the elastic modulus of the hog fuel.

The conclusion that can be drawn from the results is that the wood residues behave like an elastic solid when under the conditions present in the pile and when deflections are very small.

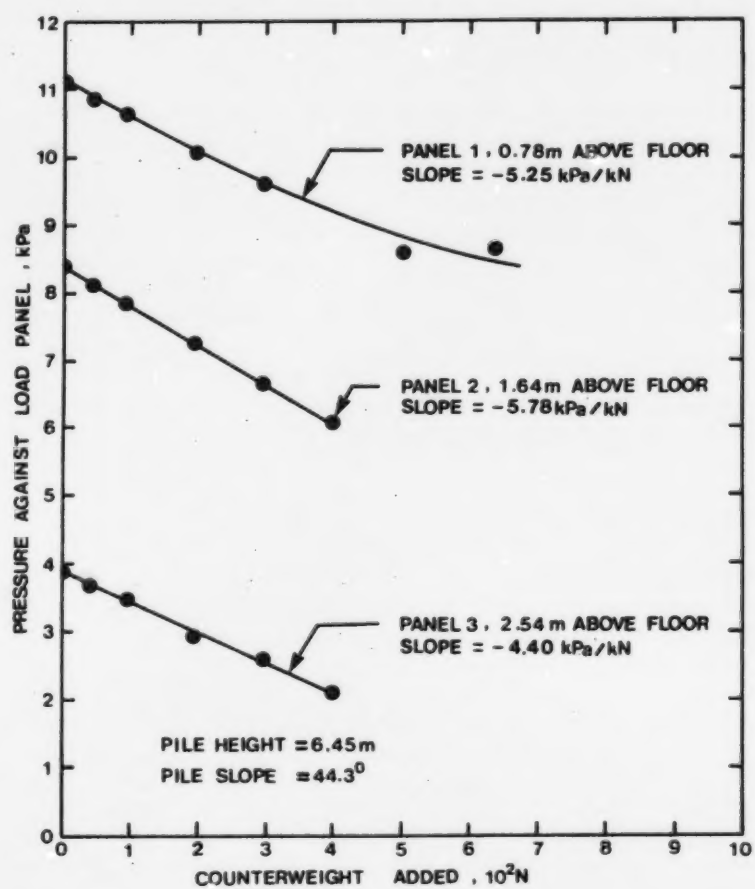


FIGURE V-11 RESPONSE OF LOAD PANEL TO COUNTERWEIGHT ADDED

VI CONCLUSIONS AND RECOMMENDATIONS

A. Pressure Sensors for Wood Residues

From the data obtained using a piezometric pressure cell and a load panel to monitor lateral pressures imposed by hog fuel at Fraser Mills, it is evident that the a piezometric pressure cell of the size tested is unsuitable for use with hog fuel. The poor reponse of the piezometric pressure cell is attributed to bridging of residues across part of the sensing surface, resulting in an anomalous pressure distribution. Bridging of residues between the wall and the load panel likely also occurred, but the impact of this condition would be minimized by the large sensing area.

It is recommended that a pressure sensor having a comparable sensing area and displacement to the load panel sensor used in these tests be used for any further monitoring of pressures imposed by coarse wood residues.

B. Thrust on Retaining Walls

For both chips and hog fuel, the normalized pressure (P/γ) imposed near the base of the retaining walls considered in this study did not increase linearly with height of material. The proportionality coefficient relating normalized pressure to height of material for the active pressure condition, k_{ah} , decreases with increasing height of material according to a semi-logarithmic relationship.

The relationship for the coefficient of active horizontal pressure imposed by green wood chips stored in a conical pile having an average surface slope of 28.4° to 32.2° was determined to be

$$k_{ah} = 0.76 - 0.311 \ln H$$

for values of H between 0.45 m and 3.3 m.

A similar relationship,

$$k_{ah} = 0.735 - 0.15 \ln H,$$

was determined for moist hog fuel stored in a roughly two-dimensional peaked pile with values of H between 0.65 m and 5 m.

The above relationships may be used to calculate normalized pressure using the equation $P/\gamma = k_{ah} H$ where γ is the packed bulk density as determined by the procedure used in this study. The relationships given for k_{ah} may only apply to pile shapes and heights and to wood residues tested in this study.

If the pile is not similar to what was used for the field tests, then an estimate of the value of k_{ah} for the base of the pile may be determined using the Coulomb equation, as long as the surface of the pile slopes at near the natural angle of repose of the material. For this calculation the internal friction angle should be taken to be equal to the natural angle of repose of the surface.

Use of the Coulomb equation for a flat pile led to values of k_{ah} for hog fuel in the age and vehicle tests of about 40% of the actual value. This would result in a corresponding under-estimation of thrust. For this reason, it is suggested that the Coulomb equation not be used to estimate pressures for flat piles unless a correction factor is included.

To determine the total thrust on a restraining wall both the pressure at the base of the wall and the distribution of pressure on the wall must be known. If the pile shape and height and the characteristics of the residues are similar to those used for the field tests, then the pressure at the base of the pile may be determined from the experimentally determined value of k_{ah} . For other sloping piles, an estimate for k_{ah} from the Coulomb equation may be used. Based on the field tests, pressure on a retaining wall can be assumed to increase linearly with depth to the calculated pressure at the base of the wall. The assumption of a linear pressure distribution led to an over-estimate of thrust by 18% for the hog fuel retaining wall at Fraser Mills, and an over-estimate of average thrust by 5.6% for the chip retaining wall at Canfor. This same assumption led to an over-estimate of the height of the centre of effort by 11% for hog fuel, and by 3.3% for chips. Hence, the assumption of a linear pressure distribution is expected to result in estimates of thrusts and moments that exceed actual values, but not unduly.

The data obtained at Fraser Mills for hog fuel after the first, second, third and ninth pile build-up indicate that cyclic build-up on dormant material leads to changes of the maximum pressure at the base of the wall, and of the pressure distribution. The largest thrust on the wall existed after the first build-up against a bare wall. The pressure distribution was found to stabilize after the third build-up. Values of k_{ah} for this series of tests for the panel nearest the floor were found to equal 0.60 after the first build-up and to reach a high of 0.73 after the second build-up. All values of k_{ah} for the four test dates were greater than 0.5, the average of four previous runs.

C. Effect of Pile Age

Aging was observed to cause an initial decrease in lateral pressure at the base of the wall, possibly due to dissipation of the effects of compaction during pile build-up at the test site. Changes of the bulk density of materials near the pile surface had a negligible effect on pressure at the base of the wall.

D. Effect of Vehicle Traffic

After initial compaction for the vehicle tests, the hog fuel behaved like an elastic solid, repeatedly reaching similar maximum pressures while the vehicle passed in front of the pressure sensors, and returning to similar base pressures as the vehicle moved away from the pressure sensors.

The best estimate of pressure near the pile surface due to a vehicle moving parallel to a retaining wall was obtained from a theoretical model that assumed equivalent line loads located along the centre-lines of the track paths. This theory over-estimated the depth of influence of the vehicle and, consequently, over-estimated thrust on the wall. Experimental data indicate that a rise in pressure on the wall occurred to a depth of less than 1.766 m for motion parallel to the wall.

Theory that assumes the presence of two point loads at the centre-point of the tracks over-estimated pressure near the surface by 9% for motion perpendicular to the wall in front of the pressure sensors. This theory over-estimates the depth of influence of the vehicle and thrust on the wall. For these tests, a pressure rise occurred to a depth of somewhat more than 1.766 m.

E. Further Work

The test program identified several study areas where further work is needed to develop more explicit relationships for design of retaining structures for wood residues. Both experimental and theoretical work is needed to better predict the effects of pile slope and height, the effects of residue characteristics, particularly particle size, and the effects of vehicle traffic.

The data obtained from this study have shown that an estimate of k_{ah} may be obtained from the Coulomb equation only when the surface of the pile slopes at near the angle of repose of the material. Systematic testing is needed to define the relationship between lateral pressure and pile slope over a full range of pile slopes. This testing should be done using normal mill residues and at full scale to ensure the data reflect typical operating conditions.

Experimental results indicate that the normalized pressure due to a height of material is affected by the size and shape of the pile. Existing theory does not explain this effect satisfactorily and, therefore, prediction of the pressure distribution and the location of the centre of effort on the wall cannot be done with certainty for piles with a significantly different size and shape than considered in this study. An assumption of a linear pressure distribution results in modest over-design for the cases considered in this study. To improve the design of common storage bins and retaining walls for wood residues, it is suggested that lateral pressures be measured for those designs not considered in this study. Of particular importance for further study are silos of cylindrical and A-frame design since these designs are widely used, but are designed according to inadequate design data.

The experimental results obtained for chips and hog fuel apply to piles of different shapes and it is therefore not possible to isolate the effect of residue type and particle size on lateral pressure. Because of the similarity of the values of k_{ah} for these two residues, the effect of differences in particle size is believed to be minimal when compared to other influential factors. Different values of k_{ah} are expected for residues having markedly different particle sizes such as sawdust and shavings. It is recommended that lateral pressures be measured for residues not considered in this study. Preferably these tests could be incorporated into a test program to monitor pressures on silo walls.

The study results indicate the depth of influence of vehicle traffic and the maximum pressure rise that can occur. By comparison with theory, the experimental data for maximum pressure rise can be extrapolated to other vehicle weights. Existing theory is unable to satisfactorily predict the pressure distribution resulting from vehicle traffic. Further theoretical analysis of this problem is recommended. Data from this study may be used to verify theoretical results.

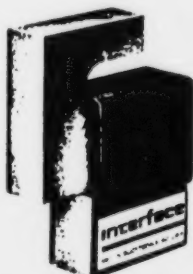
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APPENDIX I
LOAD CELL SPECIFICATIONS

Interface

ADVANCED FORCE MEASUREMENT

SUPER-MINI LOAD CELLS

Model SM-25

**Designed
for
Precision
Electronic
Force Measurement**



Model SM-1000

FEATURES

- Ultra Precision
- Excellent Linearity
- High Repeatability
- Thermally Compensated
- Low Moment Sensitivity
- Low Cost
- Easily Installed
- NBS Handbook 44 Sealable

**RATED CAPACITIES: 10, 25, 50, 100, 250, 500 and 1000 pounds
(44N, 111N, 222N, 445N, 1112N, 2224N, 4448N)**

These ultra precision strain gage load cells are designed expressly for all controlled environment, tension and compression force and weight measuring requirements. Interface's application of proprietary advanced materials technology, in strain gage and flexure design, produces load cells with the highest accuracy in the industry yet priced competitively with lower performance units.

These rugged cells have no moving parts to wear out or get out of adjustment. The specifications listed below illustrate the superior performance of Interface SM Series load cells and are a major factor in their worldwide acceptance in applications such as structural force testing, thrust measurement, steelyard rod conversions (to H-44, PTB and SIM requirements), conveyor scales, check weighers, counting and white scales, tensile testing and engine dynameters.

The Interface optional MR (Moisture Resistant) Super-Mini is now available as a cost effective method of protecting 25 thru 250 lb load cells against the effects of exposure to high humidity (up to 95% RH) and periodic condensation.

For metric applications see Metric Super-Mini Series offering 200N, 500N, 1000N, 2000N and 5000N capacities and metric mounting threads.

SPECIFICATIONS*

Non-Linearity—% Rated Output.....	±0.03
Hysteresis—% Rated Output	±0.02
Non-Repeatability—% Rated Output	±0.01
Temperature Range, Compensated—°F..... (–18 to 66°C)	0 to 150
Temperature Range, Operating—°F..... (–54 to 93°C)	–65 to 200
Temperature Effect on Rated Output—% of Reading/100°F (% of Reading/55.6°C)	±0.08
Temperature Effect on Zero—% Rated Output/100°F (% Rated Output/55.6°C)	±0.08
Temperature Effect on Zero—% Rated Output/100°F (% Rated Output/55.6°C)	±0.12
For Moisture Resistant Models	
**Creep, After 20 Min.—% Rated Output	±0.03
Overload Ratings—% Rated Capacity	
Safe.....	±150
Ultimate.....	±500
Nominal Output—mV/V.....	3
Zero Balance—% Rated Output	±1
Input Resistance—Ohms	350±3.5
Output Resistance—Ohms	350±3.5
Excitation Voltage	
Recommended—VDC	10
Insulation Resistance, Bridge to Case—Megohms	5000

*Per SMA "Load Cell Terminology and Definitions"

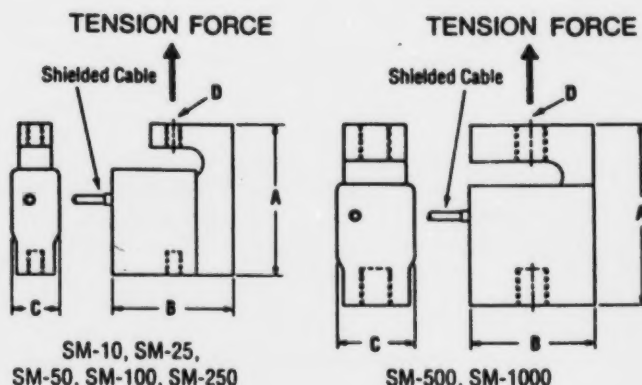
**Creep specification is determined at rated capacity. Creep performance at reduced loads is proportional to the applied load.

INTERFACE
SUPER-MINI
LOAD CELLS

SUPER-MINI LOAD CELLS

INSTALLATION DIMENSIONS

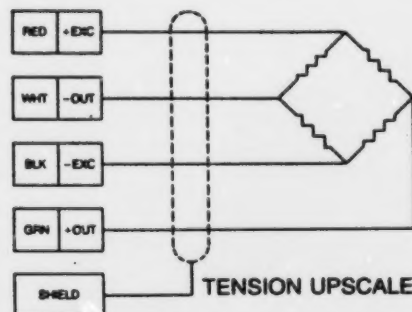
Model		A	B	C	D
SM 10, 25, 50	inch	2½	2	¾	¼-28 UNF-2B
100, 250	mm	64	51	19	¼ Deep, top & bottom
SM 500,	inch	3	2	1¼	½-20 UNF-2B
1000	mm	76	51	32	½ Deep, top & bottom



ELECTRICAL INFORMATION

SM Series is provided with a 4-conductor shielded cable (AWG 28) 5 feet (1.5m) long.

Wiring color code complies with ISA S37.8-1975 "Specifications and Tests for Strain Gage Force Transducers."



APPLICATION NOTES

1. Super-Mini load cells are designed for controlled environmental applications. In general, they can be used anywhere a readout instrument is used.
2. One diameter thread engagement is desirable—approximately ¼" (6mm) on the 10 through 250 pound ranges and ½" (12mm) on the 500 and 1000 pound units.
3. Moisture Resistant Super-Mini load cells are marked -40. These units are resistant to high humidity conditions up to and including 95% Relative Humidity and periodic exposure to condensation. The design capability is not intended for submerged operation.

4. Jam nuts may be used, however care should be exercised to not apply excessive torque across the load cell. Torque should be reacted against the load cell structure immediately adjacent to the jam nut.

Model	Jam nut torque/inch-pounds
SM-10	5
SM-25	10
SM-50	20
SM-100, 250	40
SM-500, 1000	200

TERMS AND CONDITIONS

1. **Ordering Information:** Super-Minis are ordered by specifying Series (SM) and capacity (10, 25, 50, 100, 250, 500, -1000 pounds). *Example:* SM-100.
2. **Unit Pricing:** SM-10, SM-25, \$225; SM-50, SM-100, \$160; SM-250, \$165; SM-500, \$175; SM-1000, \$195. Add \$10.00/unit for MR option. Contact factory or local Interface Representative for delivery information.
3. **Terms:** Net 30 days in U.S. dollars, FOB Scottsdale, Arizona U.S.A.
4. **Warranty:** Interface, Inc.'s standard two-year warranty is applicable to the Super-Mini Series load cell. Interface, Inc. certifies that its calibration measurements are traceable to the U.S. National Bureau of Standards (NBS).

Prices and specifications subject to change without notice.

Interface
ADVANCED FORCE MEASUREMENT

INTERFACE, INC. 7401 E. BUTHERUS DR. SCOTTSDALE, ARIZONA 85260 USA (602) 948-5555 TELEX: 688-394

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Printed in U.S.A.

APPENDIX II

DERIVATION OF THE LOAD PANEL CALIBRATION RELATIONSHIP

A simple relationship was derived to relate the force sensed by the load cell(s) to the distributed pressure applied by the wood residues. A sample calibration is derived here that applies to the load panel used at Fraser Mills during Phase I. A calibration relationship was derived for each load panel used during the tests. Differences between these relationships are slight.

The calibration relationship was derived by summing the moments about the hinges supporting the upper edge of the panel. Frictional torque from the hinges and small errors were determined from an in-field calibration of the panel.

1. Panel Specifications

Counterweight:	18.68 N
Panel Weight :	88.96 N
Panel Length :	282.6 mm
Panel Width :	612.8 mm
Distance of Load Cell Support From Bottom Edge of Panel:	25.4 mm
Distance of Counterweight From Bottom Edge of Panel:	80.5 mm

2. Sum of Moments

a) Pressure From Residues

Assume a uniform pressure distribution, P , over the area of the panel. The resultant force acts through the centroid of this area.

$$\begin{aligned}\text{Pressure} &= 0.001 P(282.6 \times 612.8) \\ &= 173.18P \text{ N}\end{aligned}$$

$$\begin{aligned}\text{Moment Arm} &= (282.6 \text{ mm} + 17.5 \text{ mm})/2 \\ &= 150.05 \text{ mm}\end{aligned}$$

$$\text{Moment, } M_1 = 25985.7P \text{ Nmm}$$

b) Friction on Panel

Two laboratory tests were done at B.C. Research to determine the friction between moist hog fuel and stainless steel. The samples were tested as received and had the following friction angles:

Hog Fuel From Fraser Mills:

Sample 1: Wall Friction Angle = 25.7°
Friction Coefficient = 0.482

Sample 2: Wall Friction Angle = 26.04°
Friction Coefficient = 0.4885

Hog Fuel From Canfor:

Wall Friction Angle = 24.88°
Friction Coefficient = 0.4638

For purposes of calculation, a friction angle of 25.89° and a corresponding friction coefficient of 0.4853 was used.

$$\text{Friction Force} = 0.4853 \times 173.18 \text{ P N}$$

$$\begin{aligned}\text{Moment Arm} &= 17.5/2 - 3.2 \\ &= 5.55 \text{ mm}\end{aligned}$$

$$\begin{aligned}\text{Moment, } M_2 &= 84.04 \text{ P} \times 5.55 \\ &= 466.4 \text{ P N mm}\end{aligned}$$

c) Panel Weight

$$\begin{aligned}\text{Moment Arm} &= 17.5/2 - 3.2 - 6.4/2 \\ &= 2.35 \text{ mm}\end{aligned}$$

$$\begin{aligned}\text{Moment, } M_3 &= 88.96 \times 2.35 \\ &= 209.1 \text{ N mm}\end{aligned}$$

d) Counter Weight

$$\begin{aligned}\text{Moment Arm} &= 17.5/2 + 282.6 - 80.5 \\ &= 210.85 \text{ mm}\end{aligned}$$

$$\begin{aligned}\text{Moment, } M_4 &= 18.68 \times 210.85 \\ &= 3938.7 \text{ N mm}\end{aligned}$$

e) Load Cell Reaction:

$$\text{Total Load Cell Reaction} = R$$

$$\begin{aligned}\text{Moment Arm} &= 17.5/2 + 282.6 - 25.4 \\ &= 265.95 \text{ mm}\end{aligned}$$

$$\text{Moment, } M_5 = 265.95 \text{ R Nmm}$$

f) Friction Torque From Hinges and Correction For
Miscellaneous Dimensional Errors

By equating the sum of the moments identified above to zero using the field data obtained by adding additional counterweights to an unloaded panel, a correction term, T, was determined. The data for this calibration are presented in the main text (Figure III-5).

$$T = -2778.2 \text{ N mm}$$

g) Calibration Equation

$$\text{Sum of Moments} = 0$$

Therefore:

$$25985.7P + 466.4P + 209.1 + 3938.7 - 265.95R - 2778.2 = 0$$

Rearranging gives,

$$P = 0.01005R - 0.0518 \text{ kPa}$$

where R is in Newtons.

APPENDIX III

DERIVATION OF THE WALL DISPLACEMENT RELATIONSHIP FOR FRASER MILLS

The deflection of the bin wall near the load panel was measured during Phase I. These deflections were estimated using a trigonometric relationship that gives wall deflection as a function of the change in distance between reference markers on the wall and a reference stake driven into the ground. The dimensions relevant to the relationship are given in Figure A-1. The deflection is assumed to be horizontal.

$$a^2 = b^2 + c^2 - 2bc \cos A \quad (1)$$

$$l^2 = \delta^2 + b^2 - 2b\delta \cos A' \quad (2)$$

Angle A' is related to angle A :

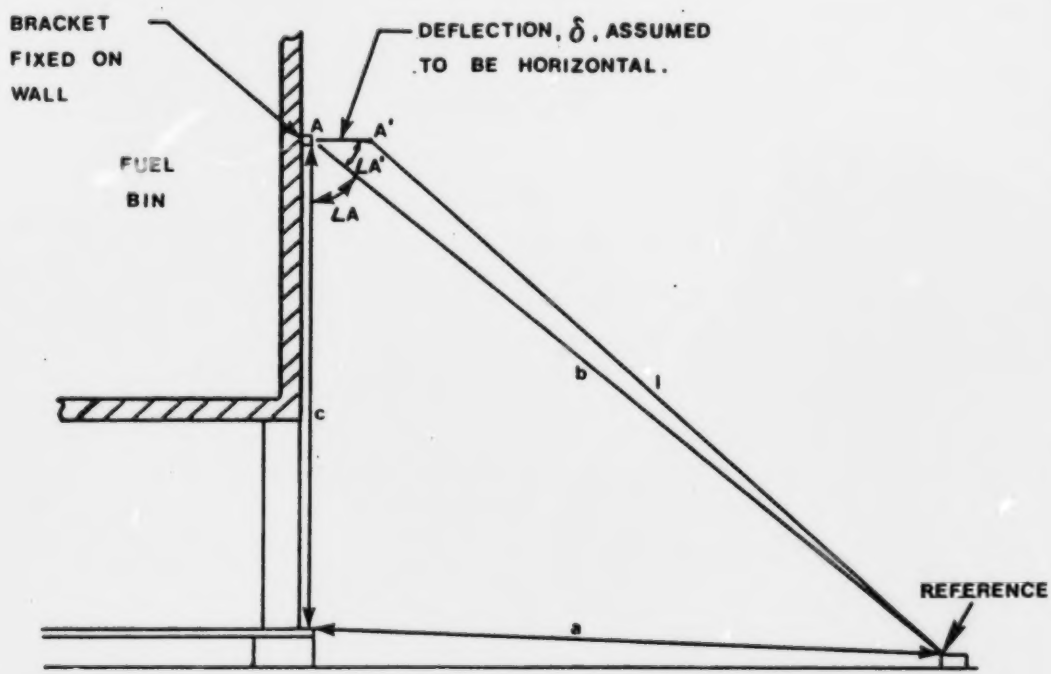
$$A' = 90^\circ - A$$

From (1):

$$A' = 90^\circ - \cos^{-1}[(b^2 + c^2 - a^2)/2bc] \quad (3)$$

The deflection, δ , is calculated by solving equation 3 and substituting this angle into equation (2) written as follows:

$$\delta = b \cos A' - \sqrt{b^2 \cos^2 A' - (b^2 - l^2)}.$$



$$\text{DEFLECTION, } \delta = b \cos(\angle A') - \sqrt{b^2 \cos^2(\angle A') - (b^2 - l^2)}$$

FIGURE A-1 METHOD USED TO DETERMINE BIN WALL
DEFLECTION AT FRASER MILLS FOR
PHASE I

APPENDIX IV

RESULTS OF SHEAR AND WALL FRICTION TESTS ON HOG FUEL

Tests were conducted to determine wall friction angles for unscreened samples of hog fuel and internal friction angles for samples of hog fuel screened to minus 25.4 mm. The internal friction angles were done on screened samples, since there was an upper limit on the particle size that could be handled by the test equipment.

Results for internal friction angle are given in Table A-1 along with other test data and sample characteristics.

Table A-1
FLOW PROPERTIES OF HOG FUEL SAMPLES

SAMPLE DESCRIPTION	NORMAL STRESS (g/cm ²)	SHEAR STRESS (g/cm ²)	UNCONFINED YIELD STRESS (g/cm ²)	INTERNAL FRICTION ANGLE (degree)	COHESION (g/cm ²)
1. <u>Fraser Mills</u>	27	40.0	44.2	59.41	4.95
Wall Friction Angle ^a 25.7°	48.1	71.6	84.0	59.41	9.39
	59.9	86.6	94.0	59.41	10.51
	81.8	111.2	120.3	59.41	13.45
	98.7	140.4	152.8	59.41	17.09
	115.6	151.3	163.6	59.41	18.29
2. <u>Fraser Mills</u>					
Wall Friction Angle ^a 26.04°					
3. <u>Canfor</u>	27	38.6	49.6	57.5	5.84
Packed Density 502 kg/m ³	48.1	66.6	64.0	57.5	7.55
Moisture Content 68.3%	59.9	79.9	105.3	57.5	12.41
Wall Friction Angle ^a 24.88°	81.8	106.1	126.1	57.5	14.86
	98.7	124.8	136.2	57.5	16.05
	115.6	143.5	164.2	57.5	19.35

^a on stainless steel

APPENDIX V

LATERAL PRESSURE FOR LINE LOAD AND POINT LOAD APPROXIMATIONS OF VEHICLE TRAFFIC

Calculations to determine lateral pressure on a retaining wall were done for each of two simple approximations to the load imposed on the pile by the bulldozer used in the vehicle tests. One model assumed the load applied by the bulldozer could be approximated by two infinite line loads running parallel to the wall at the position of the centerline of the tracks. The other model assumed two point loads directly in front of the pressure sensors at the position of the center of each track.

1. Line Load Approximation

Two empirical formulae for determining the increase in lateral pressure, P , on a retaining wall due to an infinite line load, q (kN/m), parallel to the retaining wall were given by Bowles:

$$m \leq 0.4 \quad P = \frac{q}{H} \times \frac{0.203n}{(0.16 + n^2)^2}$$

$$m > 0.4 \quad P = \frac{4}{\pi} \times \frac{q}{H} \times \frac{m^2 n}{(m^2 + n^2)^2}$$

where H is the height of a pile with a flat surface, mH is the distance of q from the retaining wall, and nH is the depth at which the pressure, P , corresponds (Figure A-2).

From the vehicle test we have:

$$q = \frac{\text{weight of bulldozer}}{\text{no. of tracks} \times \text{track length}}$$

$$= \frac{74.312 \text{ kN}}{2 \times 2.67 \text{ m}}$$

$$= 13.92 \text{ kN/m}$$

Track 1 = 0.725 m from the wall. Therefore,

$$m = \frac{0.725 \text{ m}}{0.355 \text{ m}} = 0.204 < 0.4$$

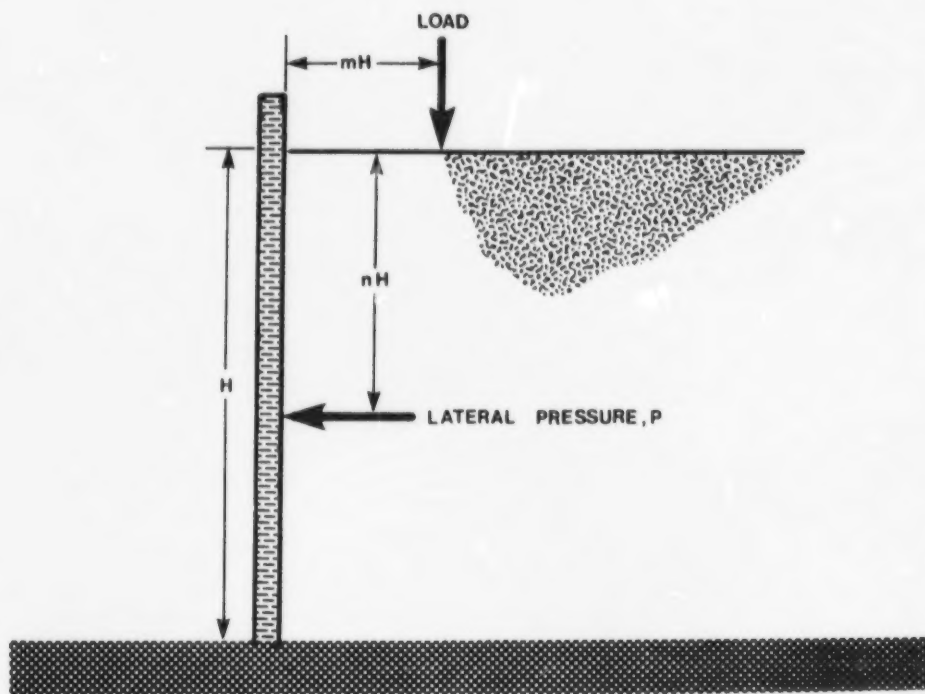


**FIGURE A-2 TERMINOLOGY FOR THEORETICAL ANALYSIS
OF PRESSURE DUE TO VEHICLE TRAFFIC**

Track 2 = 2.075 m from the wall. Therefore,

$$m_2 = \frac{2.075 \text{ m}}{0.355 \text{ m}} = 0.585 > 0.4$$

PANEL	n	P ₁ (kPa) m ₁ = 0.204	P ₂ (kPa) m ₂ = 0.585	Total P (kPa) P ₁ + P ₂
1	0.808	0.974	1.395	2.369
2	0.503	2.349	2.427	4.776
3	0.198	3.975	2.327	6.302

2. Point Load Approximation

Two empirical formulae for determining the increase in lateral pressure, P, on a retaining wall due to a load, V, were given by Bowles:

$$m < 0.4 \quad P = \frac{0.28 V}{H^2} \times \frac{n^2}{(0.16 + n^2)^3}$$

$$m > 0.4 \quad P = \frac{1.77 V}{H^2} \times \frac{m^2 n^2}{(m^2 + n^2)^3}$$

where H is the height of the pile with flat to surface, mH is the distance of the point load, V, from the wall and nH is the depth at which the pressure, P, corresponds.

From the vehicle test, we have:

$$V = \frac{\text{weight of bulldozer}}{\text{no. of tracks}}$$

$$= \frac{74.312 \text{ kN}}{2}$$

$$= 37.156 \text{ kN}$$

$$H = 3.55 \text{ m}$$

Track 1 = 0.725 m from the wall. Therefore,

$$m_1 = \frac{0.725 \text{ m}}{0.355 \text{ m}} = 0.204 < 0.4$$

Track 2 = 2.075 m from the wall. Therefore,

$$m_2 = \frac{2.075 \text{ m}}{0.355 \text{ m}} = 0.585 > 0.4$$

PANEL	n	P_1 (kPa) $m_1 = 0.204$	P_2 (kPa) $m_2 = 0.585$	Total P (kPa) $P_1 + P_2$
1	0.808	0.003	1.183	2.186
2	0.503	2.965	2.143	5.108
3	0.198	4.094	1.262	5.356

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